Thermal Parameters of Beech Wood Dust

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Wood as a flammable material can be characterized by fire and technical parameters, such as initial temperatures of its degradation, caloric heat, caloric value, and explosion limits. These parameters reflect the suitability of using a particular type of wood for construction purposes or as biofuel. This article presents selected characteristics of beech wood (*Fagus sylvatica* L.*)* particles (dust fractions) on the basis of continual thermal loading. The thermal properties of beech particles were characterized by thermogravimetric analysis (TG), which indicated different thermal degradation patterns for different dust fractions. The beech wood dust consisted mainly of fractions of 80 µm, 32 µm, and < 32 µm, which was 70.50% of the sample. These fractions form explosive mixtures with air, and their thermal degradation involves only one step.

Keywords: Wood dust beech; TG; DTG analysis

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INTRODUCTION

Wood is an important natural organic material in society. Therefore, it is necessary to accept the fact that wood in any form (raw material, dust, or material based of wood) cannot remain unchanged when exposed to higher temperatures. If wood is used as a construction material, this property is a disadvantage, but it is an advantage when wood is used as a fuel. It is necessary to know specific heat parameters of wood to evaluate the behavior of wood during exposure to heat.

Beech (*Fagus sylvatica* L.) represents 29% of the wood in Slovak forests. Beech timber is a typical Slovak raw material for the manufacturing of plywood, chipboard, and fibreboard. It has been used also to produce paper and pulp, which significantly reduces the availability of beech wood for fuel (Dittmara *et al*. 2003).

Beech and oak (*Quercus petraea* [Matt.] Liebl) are the most widespread deciduous trees in Slovakia. The physical, mechanical, and fire-burning properties of beech wood are presented in Table 1. In general (*e.g.*, in contrast to spruce), this wood is very promising, especially in the context of climate change in Central Europe (Pajtík *et al.* 2011)

The mechanical processing of wood (sawing, planning, milling, and grinding) creates a large quantity of dust and chips, which increases the risk assessment by representing a potential danger of fire or explosions (Krentowski 2015). Dust created by wood working, especially grinding, is flammable and can form an explosive mixture with air (Amyotte and Eckhoff 2010; Zigo *et al*. 2014). The timber industry is a sector in which dust is generated as an undesirable waste (Krentowski 2015; Top *et al*. 2016). It can be supposed that the risk of an explosive wood dust mixture occurring depends on the size of

the wood dust particles.

Table 1. Physical, Mechanical, and Burning Properties of Beech Wood

Physical, Mechanical, and Fire and Burning Properties of Beech Wood	Value Valid for 15% Wood Humidity
Density	675 $kg \cdot m^{-1}$
Flash-ignition temperature [STN 64 0149]	360 - 370 °C
Spontaneous-ignition temperature [STN 64 0149]	400 - 410 °C
Oxygen index [STN 64 0756]	25.5%
Gross heat of combustion [STN 44 1352]	19.8 $MJ \cdot kg^{-1}$
Optical density of smoke	7.3 $m^2 \cdot kg^{-1}$
Mass burning rate	0.066 $kg \cdot m^{-2}$

Note: Data from MISSR (1984)

The flash-ignition temperature is a key parameter evaluating the risk of initiation of raise dust. It is monitored in the prescribed test facility (furnace), according to STN EN 50281-2-1: 2002 (replacing STN 64 0149), where the raise sample of wood dust is exposed to radiant heat at the appropriate ambient temperature. Tureková (2008) investigated specimens of raised dusts of oak, beech, spruce, and mixtures removed from the timber working. After saturating, she used samples of dust below 71 μm. The highest flash-ignition temperature had a sample of beech dust (390 ° C).

The fractions with a larger size have a tendency to settle. The turbid dust forms microfractions with particles of less than 100 μm (Mračková and Tureková 2016). These particles are typically found when sanding wood, which is the most essential technological operation of each timber product before its final surface finishing. Different types of wide-belt sanders, narrow-belt sanders, special sanders, and hand sanders (belt, disk, and vibration) with various ways of extraction, are found in furniture establishments (Očkajova *et al.* 2014). Modern devices have a built-in vacuum system, which removes wood dust from the operation. However, not all operations have the latest technology, resulting in dust in the work area. Similarly, with the use of hand-held electric sanders, even with the inclusion of a built-in extraction system, its production is not as effective as a central extraction. The amount of incipient dust, size, and shape of individual dust particles depend on the particle size distribution of the grinding tool, pressure of the grinding tools on grinding material, grinding speed, ground material, and grinding direction (Abbasi and Abbasi 2007; Eckhoff 2009).

Wood dust is a type of biomass that can be used as an alternative fuel and renewable energy source (Rowell 2012). Rohr *et al.* (2015) assessed the potential concerns associated with the use of biomass fuels during combustion in terms of health and safety as well as the risk of explosion.

The test methods to characterize flammability and explosibility are described in national and international standards (Garcia *et al.* 2016). The new standard ISO/IEC 80079-20-2 (2016) describes the methods for determining whether a material exhibits the properties of a combustible dust as well as the explosion characteristics of combustible dusts. These test methods identify potential ignition sources of equipment for use in classified areas due to the presence of combustible dust (Garcia *et al.* (2016). Some tests include the minimum ignition temperature (MIT), the lowest temperature at which the dusty sample starts to ignite, and the lower explosion limit (LEL), which is the lowest concentration at which an air/dust mixture is potentially explosive. In general, it is

expressed in terms of weight units by air volume unit and minimum ignition energy (MIE) as the minimum amount of energy required for igniting a dust cloud, determined in mJ.

Garcia *et al.* (2016) offered thermal susceptibility tests including thermal analysis. This information describes the thermal behavior of solids and determines their self-combustion tendency.

Thermogravimetric analysis (TGA) is a fast method for estimating changes in lignocellulosic materials during thermal degradation in laboratory trials (Alfredsen *et al.* 2011). In isothermal (static) thermogravimetry, the sample is heated at a constant temperature; in un-isothermal (dynamic) thermogravimetry, the sample's change in weight is monitored in relation to time and temperature. In this case, the temperature increases at a certain linear speed, the speed of heating ($°C \cdot min^{-1}$) (Lyon *et al.* 2007). TGA curves show the relationships between the growth and the decline of weight to temperature. Thermal analysis allows researchers to monitor reactions, speed of degradation, weight decline, change of degradation temperatures, and changes in exothermic and endothermic effects. The thermogravimetric curve allows evaluation of its horizontal parts, which are characterized by constant weight. Additionally, it can be evaluated by those parts of the curve where steepness characterizes the speed of weight change, and it goes through a maximum point ($dm/dt_{maximum}$) (Tabari *et al.* 2012).

Research on beech as solid fuel (biomass) focuses on the monitoring of flammability parameters (*e.g.*, flash point, ignition temperature, and combustion heat) according to standardized procedures (Torrent *et al.* 2016). Wood dust resulting from processing has a specific behavior. Beech dust mixed with air is explosive. Explosive concentrations are determined by a standardized method. If dust settles "on equipment within an industrial plant," that might be a form of fire hazard. Thermal degraded wood dust is not treated with standardized methods. For research purposes, TGA and derivative thermogravimetric (DTG) analysis are used to quantify the thermal degradation of wood dust during thermal loading. The behavior of beech wood dust is affected by particle size. Beech wood dust was separated into fractions. The fractions up to 250 μm are a maximum of 1% of the beech dust sample (Markova *et al.* 2016). Other lower fractions were exposed to heat for thermal degradation analysis.

This article focuses on the thermal degradation parameters of wood dust beech (< 125 μm) during continuous heat loading. The properties related to thermal degradation of selected woods were assessed. The study describes the general characteristics of thermal analysis (TGA, DTG) and wood sample features. Furthermore, it describes the procedure for determining the selected thermal characteristics, including flash-ignition temperature, mass loss rate, and ignitability of material exposed to continuous heat loading.

EXPERIMENTAL

Material and Methods

Three folders were arranged for the preparation of beech wood dust with dimensions (300 x 50 x 50 mm) for beech wood species that were dried to a moisture content of about 8 to 10%. The sample was selected with regard to their most frequent industrial processing and furniture establishments. In wood processing companies, beech is a frequently manufactured wood.

Preparing beech wood samples

Wood dust samples were prepared using a BOSCH pss 200ac hand orbital sander. Samples were prepared by a specialist in grinding. The pressure of the grinding surface of the component, grinding speed, and grinding direction (cross) were as close to realistic industrial conditions as possible. Sandpaper was used with grain size P 80 in experiments (P 80 Norton H231; Zvolen, Slovakia). Figure 1 presents a prepared sample.

Fig. 1. Beech wood dust sample after grinding with sandpaper

The dust was collected in the manual extraction equipment pocket of belt sanders, from where it spilled into plastic bags. The bags were carefully sealed to maintain the moisture of obtained dust. Approximately 300 g of dust was obtained from each folder, which was mixed and used for the preparation of the sample (1 kg). This was the basis for the granulometric analysis, TG, DTG, and the determination of lower explosion limit.

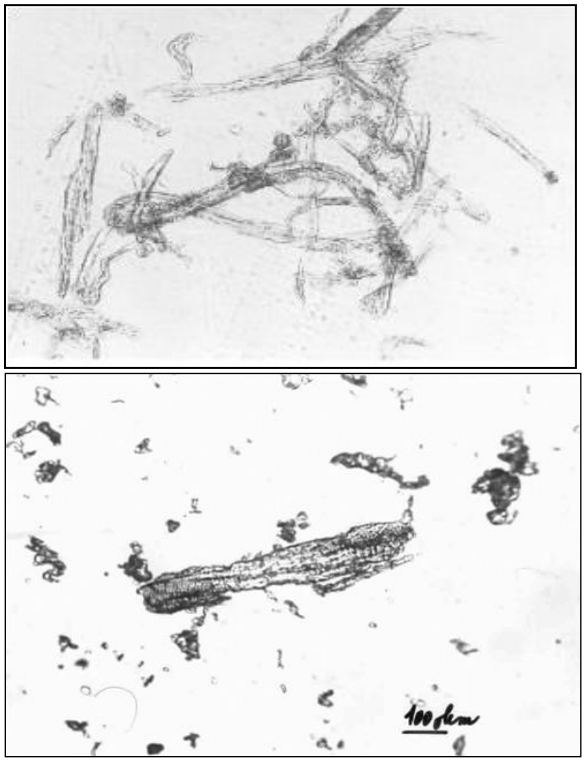

Fig. 2. Microscopic detail of beech wood dust sample at 100 µm

Sieve analysis was carried out on an automated vibratory screening machine Retsch AS 200 control (Zvolen, Slovakia); a set of control stainless steel sieves, diameter of sieve 200 mm, height 50 mm, diameter of sieve mesh 0032; 0063; 0:08; 0125; 0.250; 0.5; 1; 2 (mm). The residues on each sieves and bottom were weighed on a digital laboratory balance Radwag WPS 510 / C / 2 (Zvolen, Slovakia) to an accuracy of 0.001 g. The sieving parameters were an amplitude 2 mm/(g), with an interval of 10 s, and a time of 20 min. The process was performed according to ISO 3310-1 (2007).

Samples of beech dust were steeped in Euparal medium prior to microscopic observation. An Olympus BX 50 light transmission microscope (Zvolen, Slovakia) was used with 100× to 200× magnification of the wood dust structure (Fig. 2).

Morphological samples; Fagus sylvatica - Beech

In wood processing companies, beech can be considered among most often manufactured wood. The inventory of beech wood represents 29% in Slovak forests. It belongs to the group of diffuse-porous woods.

Thermogravimetry

The TG and DTG analyses were conducted on a Mettler TA 50 (Bratislava, Slovakia) device and evaluated by appropriate software. Thermogravimetry and DTG curves were calculated from the measurements. Weight changes were given in percentage from original sample weight. Thermogravimetric analysis was performed on a Mettler STARe SW 01/09 (Bratislava, Slovakia), with evaluation on relevant software. Samples (Table 2) were indexed as beech - raw materials and BK + number particular size (for example, 125 µm particles were labeled BK 125).

Table 2. Basic Features of Wood Dust Beech Samples Analyzed in an Air Atmosphere

Wood Dust Beech Samples	Size of Fraction (µm)	Measured Moisture (%) before TA	Specified Density of Samples ($kg \cdot m^{-3}$)	Rate of Loading (°C/min)	dm/dt (mg/s)	Thermal Range (°C)
Beech	X	6.2	675	10	0.01	20 to 1000
BK 125	125	6.8	X			
BK 80	80					
BK 63	63					
BK 32	32					
BK < 32	< 32					

X, not stated

RESULTS AND DISCUSSION

Determination of Particular Sizes (Fractions) of Wood Dust Beech

The results of the sieve analysis were evaluated by using distributive columns of selected samples of wood dust. The percentage sums of obtained values had less weight compared with the samples from the loss during sorting. The obtained distributive columns (Fig. 3) define the dependence of proportional representation of weight of certain grain sizes (fractions) in the analyzed group of natural ground.

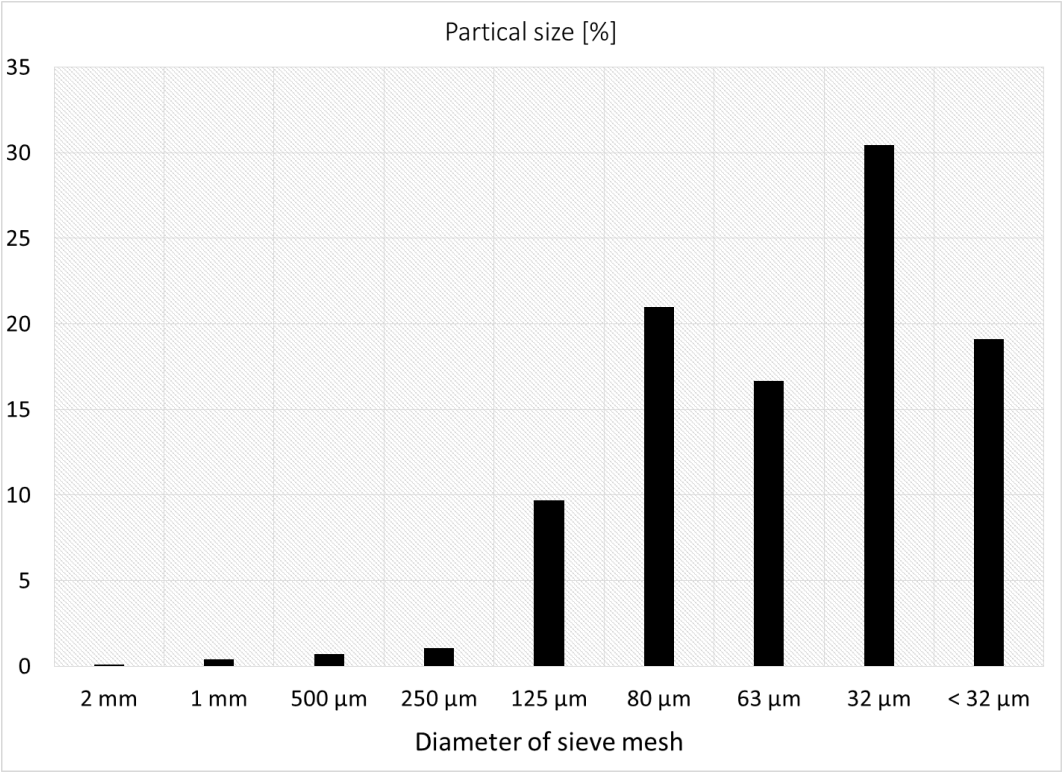

Fig. 3. Distributive granularity columns of wood dust beech samples

Results of Thermal Analysis

The most common method used to investigate thermal decomposition is thermogravimetric analysis; the thermal stability of wood has been evaluated with the TG data (Lowden *et al.* 2013). Table 3 shows that the starting level of degradation representing the drying processes, or water evaporation, from the analyzed sample. The 63 µm and 125 µm fractions had the same behavior as raw beech wood, with two stages of thermal decomposition (Fig. 4). The particles of 80 µm, 32 µm, and < 32 µm had only one stage of thermal decomposition (Table 3).

Table 3. Parameters of DTG Analysis

Wood Dust Beech Samples	Drying Process			Thermal Degradation Processes						
				I. step			II. step			
	Thermal interval (°C)	T_p (°C)	Δm (%)	Thermal interval (°C)	T_p (°C)	Δm (%)	Thermal interval (°C)	T_p (°C)	Δm (%)	$C_{rezist.}$ (%)
Beech	25 -104	60	3.40	260-350	320.3	74.26	350-500	427.0	23.99	0.88
BK 125	25 - 68	68	5.67	240-320	308	67.14	320-413	402	23.86	2.77
BK 80	25 - 68	68	5.84	232-338	304	91.45	X	x	x	2.16
BK 63	23 - 60	68	5.99	225-310	308	67.24	310-405	402	24.99	1.79
BK 32	30 - 68	68	6.25	235-339	308	91.52	x	x	x	1.67
BK < 32	25 - 67	67	5.96	241-338	306	91.88	x	x	x	2.43

The most numerous fractions in the beech dust sample were 32 µm and < 32 µm, which was < 49.6% of the whole weight of the sample. The quantity of particles under 100

µm in beech dust sample was 87.1%. The least abundant fractions were fractions 2 mm and 1 mm (0.5% of the total sample weight of beech wood dust). These results corresponded with a previous report by Očkajová and Banski (2013), which studied the quantity of particles under 100 µm in wood dust samples and presented the following results: 92.0% for beech (granulity 80), 85.1% for pine (granulity 80), and 95.0% for spruce (granulity 120).

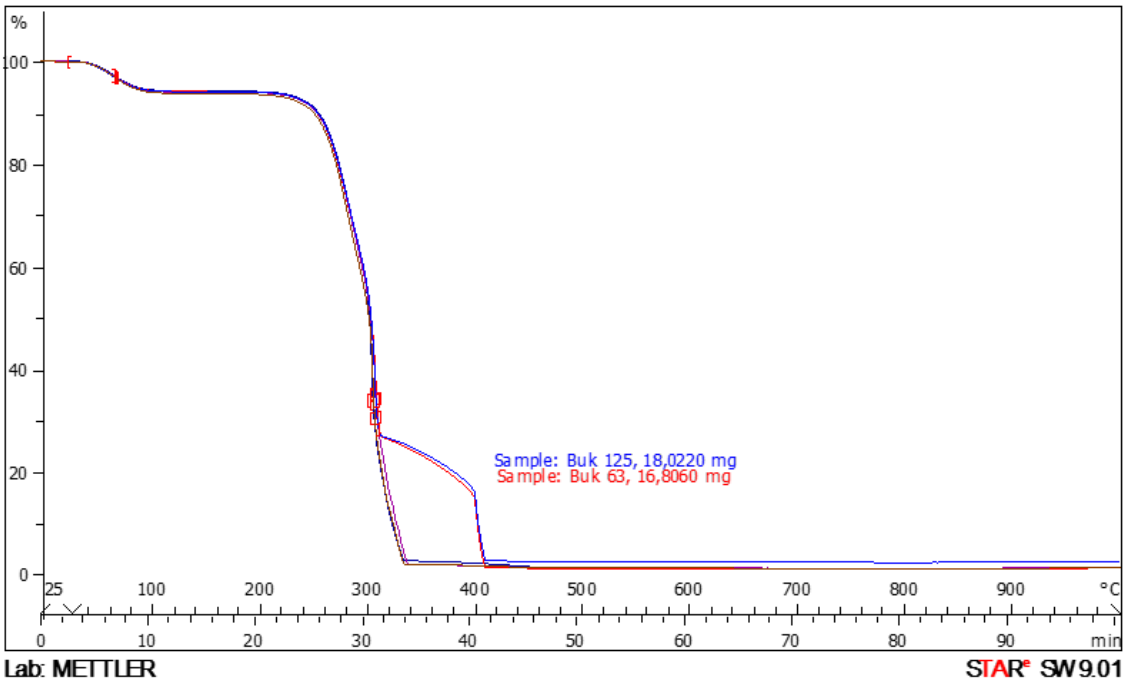

Fig. 4. TG and DTG curves of beech wood dust samples

Mračková and Tureková (2016) provided a statistical evaluation of wood particles of palisander (*Jacaranda mimosifolia* D. Don) and oak (*Quercus robur* L.*).* Their dust samples were taken from furniture production, and their measurements were conducted by laser analyzer. Their results were similar to the results presented here. The most numerous particles were in the fractions up to 100 µm (Mračková and Tureková 2016).

Increasing percentages of dust fractions represent a greater risk of explosive dust, which is an air mixture formation in an enclosed workplace. According to ISO 3569 (1995), based on the size of the particles, dust is classified into a very fine powder, designated as A D2 (0.07 to 0.40 mm), fine dust D1 (0.50 to 3.50 mm), fine-grained dust C (3.60 to 13.0 mm), medium grained B (14.0 to 75.0 mm), coarse-grained (more than 75.0 mm), and irregularly shaped fibrous dust particles E (Dzurenda and Orlowski 2011). In all tested samples, very fine and fine dust were the dominant components. In terms of the explosion risk, the fractions of 80 µm, 32 µm, and < 32 µm with an optimal proportion of air are considered as a fuel. The risk of explosion increases with an increased proportion of very fine dust. Finer dust results in a higher maximum explosion pressure and the maximum rate of explosion pressure rise (brisance), and thus a lower ignition energy is required to initiate the dust-air mixture.

Thermal analysis allows critical temperature assessments during the monitoring of weight decline during the dynamic heating of a sample. The T_p value is the temperature

where the given process is the most rapid. The Δm value represents weight decline in percentage at a given temperature scale, and WG represents percentage rest from the sample during the given thermal process.

In Fig. 4, there is a temperature interval from 41 °C to 107.6 °C that meets the technical range of drying processes. Only processes I and II (Table 4) describe the thermal degradation of wood samples, and they confirm the theory of two-stage wood degradation (Lowden *et al.* 2013). Pinto *et al.* (2016) showed *via* TGA that their analyzed wood species were stable up to 250 °C.

Based on the set temperatures of decomposition and within the frame of fractions, the decomposition temperature was comparable at the first stage (Table 4). However, the temperatures of the raw beech were higher than the mentioned temperatures of beech dust fraction decomposition. This fact confirmed a lower thermal susceptibility to the ignition of wood dust samples. The decomposition temperature in the second step for the fractions 63 µm and 125 µm were also comparable.

Martinka *et al.* (2014) showed a substantial impact of external conditions and the particle size of dust clouds forming the minimum ignition temperature; the minimum ignition temperature of turbid wood dust increased linearly with increasing particle size.

In the first stage of the beech wood dust sample decomposition, there was comparatively lower weight loss in fractions 63 µm and 125 µm. Weight loss in the second stage of decomposition was 25.0% for fraction 63 µm and 24.9% for fraction 125 µm. The fractions of 125 µm had the highest weight loss (WL) remained and the fractions of 125 µm had the smallest one. The fractions of 80 µm (sample BK 80), 32 µm, and < 32 µm behaved like dust-air mixtures. Heat exposure occurs probably by their initiation at 308 (sample BK 80) as well as in raw samples. The initiating effect can be characterized as an explosion during which 91.4% by weight of the sample (BK 80) (Table 4) is burned.

Thermogravimetry tests measures the weight of the sample as a function of its temperature when it is heated (Alfredsen *et al.* 2011). The procedure was carried out from 20 °C to 1000 °C with a heating rate of 10 °C·min^{-1}. The data obtained are plotted as a weight loss *vs*. temperature graph, and three main parameters are obtained by studying this graph: the induction temperature (IT), temperature at which the oxidation reaction starts to speed up; the maximum weight loss temperature (MLT), representing the yield of volatiles due to the pyrolysis process, and the weight loss (WG) corresponding to the thermal degradation samples can experience in their first stage of heating and oxidation. Popescu *et al.* (2011) described several parameters that were evaluated for each step of mass loss: the "onset" temperature (T_i), the temperature corresponding to the maximum rate of mass loss (T_m), and the temperature corresponding to the end of stage (T_f) (Table 4).

Table 4. DTG Analyses of Beech Samples

Wood Dust Beech Samples	First Process					Second Process			
	IT [min]	T_i [°C]	T_m (MLT) [°C]	T_f [°C]	weight loss [%] (WG)	T_i [°C]	T_m (MLT) [°C]	T_f [°C]	weight loss [%] (WG)
Beech	34	300	320	350	77.66	350	427	500	23.99
BK 125	28	290	308	320	72.71	390	402	413	23.86
BK 80	27	300	304	338	97.29				
BK 63	28	290	308	310	73.23	310	402	405	24.99
BK 32	28	280	308	339	91.52				
BK › 32	24	260	306	338	91.88				

Wood as a whole material undergoes a complex degradation scheme, which is greatly affected by its physical nature. During the thermal decomposition of wood, small molecules are eliminated, eventually leaving a charred mass. Noncombustible products, such as carbon dioxide, traces of inorganic compounds, and water vapor are produced up to 130 °C (Popescu *et al.* 2011). In this study, the drying process was over quickly (25 to 68 °C). At approximately 150 °C, some components begin to break down chemically; low temperature degradation at low rate occurs in lignin and hemicelluloses. The mass loss between 300 and 500 °C corresponds to the degradation of cellulose, the pyrolytic degradation of lignin *via* fragmentation of inter-unit linkages, and the condensation of aromatic rings (Popescu *et al.* 2011).

The temperature peaks express the devolatilization of hemicelluloses and the decrease of amorphous cellulose by Popescu *et al.* (2011) at the temperature of 308 °C. Measured temperature decomposition (T_m) of beech dust samples has the equivalent values (Table 4). The induction time (IT) of dust samples was smaller than raw beech and also T_i, but MLT dust samples were similar.

Lizhong *et al.* (2003) tested four kinds of wood (oak, kempas, cherry, and beech) with a cone calorimeter (Cone 2A) under weaker and stronger heat fluxes. The obtained critical ignition temperatures wood was in the range 190 to 310 °C. Lizhong *et al.* (2003) had more differences than the current TGA and DTG analyses.

CONCLUSIONS

1. Fractions 32 μm and < 32 μm were most numerous in beech wood dust, representing over 50%. Their thermal loading caused thermal degradation of over 90% of the sample at a relatively low temperature (260 °C). This result confirms the increased risk of adverse events.
2. Fraction 80 μm thermally degraded also in one step in the whole content of the sample (the rest was ash).
3. Based on the other results of the TG analysis of samples of beech wood dust, the most numerous fractions of beech wood dust were 80 μm and 32 μm. The thermal decomposition of samples of beech wood dust fraction in the size of 80 μm and 32 μm occurred in one step.
4. Temperature values in the first phase of thermal decomposition for all dust samples ranged between 304 and 308 ° C. The values were much lower than the raw beech sample (320.3 ° C).

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