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CONTENT OF RESPIRABLE AND INHALABLE FRACTIONS IN DUST CREATED WHILE SAWING BEECH WOOD AND ITS MODIFICATIONS

*This paper presents the results of the granulometric analysis of sawdust, created during the sawing of modified and unmodified beech wood with a circular saw. The aim of this work was to analyze the effect of the treatment of beech wood (*Fagus sylvatica *L.) on the content of respirable and inhalable particles in sawdust generated during the sawing process using a modern circular saw. Different methods of particle-size determination were used. The results obtained from the sieve analysis prove that the sawdust created during the cutting of DMDHEU was finer than the sawdust from native beech and other modified materials. It was also discovered that the dust created during the cutting of Bendywood was finer than when machining native beech and Lignamon. There was an increase in the share of fine fraction in the range of granularity $x < 100$ μm at the expense of the fraction $x = 0.25$–1 mm. The properties of Lignamon are primarily based on the properties of raw wood material, therefore this modified material had a similar cumulative particle-size distribution to the native beech dust.*

Keywords: beech, modified wood, wood dust, circular saw blade, particle-size distribution

Introduction

During woodworking some amount of dust is produced as waste. Wood dust is an assembly of individual particles whose shape and size depend on the properties of the worked wood material and working parameters. Dust created during woodworking and dispersed in the air presents a great problem in the working

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environment of the wood machining industry. Dust is an occupational hazard for workers employed at woodworking machines and they run the risk of disorders of the human respiratory tract and mucous membranes. Wood dust exposure is also causes nose and eye irritations. Protection against wood dust should be based on detailed knowledge of the sources of dustiness in the air around woodworking machines [Dutkiewicz, Prażmo 2008]. Thus, it is necessary to determine the mass rate of generated dust and its particle-size distribution in order to evaluate the health hazard created while working with different wood materials from dust particles dispersed in the air.

Different working operations and wood materials are the reason for the changeability of the total dust created and the rate of the concentration of inhalable or respirable particles in the air [Beljo-Lučić et al. 2011]. Beech wood is one of the most hazardous materials used in furniture and wood product manufacturing [Baran, Teul 2007; Jacobsen et al. 2010]. Recently, modification technology has made it possible to obtain new materials based on solid wood. This technology changes the properties of the wood. It influences the working parameters of these materials and the properties of the wood dust generated [Barcík, Gašparík 2014]. Dolny et al. [2011] found that dust particles with smaller dimensions are generated during the sanding of thermally-modified oak wood than during the sanding of natural oak wood. A similar conclusion was reached by Dzurenda, Orłowski [2011] where sawdust generated during the sawing of modified and unmodified ash wood on a sash gang saw. There has been a development in wood sawing technology aimed at increasing the raw material yield, decreasing energy consumption and improving the working precision and the quality of the sawed surface. This development in woodworking techniques is represented by narrow-kerf sawing using a thin band of circular saws (Wintersteiger, A), thin-cutting band saws (Neva, CZ; Wintersteiger, A) and narrow kerf sash gang saws (PRW15M, PL) [Orłowski 2007, 2010]. However, narrow-kerf sawing operations can be a source of increased air dustiness because the particle-size of the sawdust generated may be smaller than during the sawing using traditional saws.

The aim of this work was to analyse the effect of the treatment of beech wood (*Fagus sylvatica* L.) on the content of respirable and inhalable particles in sawdust generated during the sawing process using a modern circular saw. Different methods of particle-size determination were used.

Material and methods

The experiment was performed on a modernized experimental testing device used to research circular sawblade cutting [Kopecký, Rousek 2012]. This device simulates the conditions of circular-saw blade cutting in actual operation as closely as possible. The parameters of the cutting process (cutting force F_c, feed force F_f and workpiece feed velocity v_f) were recorded by sensors installed in the measuring stand. This experimental equipment also makes it possible to measure the vibrations of the circular sawblades and their noise. For research into dustiness, it was necessary to equip the stand with a sucking device (URBAN Technik, CZ) and a GTE device (Gravimetric Techniques Emissions, TESO Praha, CZ) for isokinetic sampling of the dust.

Research into dustiness primarily obtains information on the machine dust emission where knowledge of the grain size composition of the sawdust and dust is known. It is suitable to select cutting conditions in such a way that the machine dust emission is expressed by a functional relation to the removed chip thickness. Sampling of the sawdust and dust is carried out isokinetically. The actual air sampling is closer to the isokinetic sampling most when it is carried out by a probe with optimum dimensions and shape, and if the air velocity in the sampling probe nozzle is identical (as for size and direction) with the velocity of air in the place of measurement.

Sampling was carried out by an isokinetic gravimetric GTE set consisting of a sampling isokinetic probe (2), a TESTO (5) flowmeter, a cyclone pre-separator of sawdust and dust (6), a sucking device and BECKER connecting pipe (fig. 1). The sampling probe construction has to guarantee preferably the smallest disturbance of the air flow pattern before the nozzle. The shape and design of the face edges of the nozzle are especially important to minimize any disturbance of air flow at the probe entry. The sucking device has to guarantee controllable air flow through the sampling device so that the conditions for isokinetic sampling are maintained at every point of the process. The sampling period is determined on the basis of the number of sampling points, in the cross-section measurement and by the period of sampling at one point. The method of sampling has to be in accordance with the ČSN ISO 9096 standard.

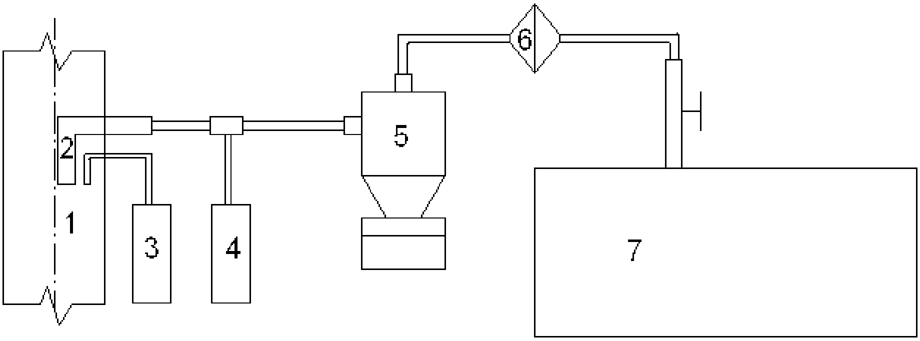

Fig. 1. Isokinetic gravimetric set: 1 – piping, 2 – isokinetic probe, 3 – Prandtl's tube and measuring device (eg. TESTO 512), 4 – configuration for speed measurements in isokinetic unit, 5 – cyclone pre-separator, 6 – configuration with filter, 7 – Becker vacuum pump [Gerek 2010]

Measurements were taken of samples of native beech $\rho = 684$ kg·m^{-3}, hydro-thermally treated, compressed Bendywood beech $\rho = 739$ kg·m^{-3} [What is Bendywood® 2014], Lignamon beech compressed and modified by ammonium $\rho = 1066$ kg·m^{-3} and chemically-treated beech DMDHEU $\rho = 707$ kg·m^{-3} [Bollmus et al. 2009; Pařil et al. 2014; Troppová et al. 2013], which were used in the experiment. The rectangular prisms (700 × 120 × 21 mm) were dried (moisture content approximately 6.9%) and unified in the same thickness e = 21 mm on a thicknesser.

The dustiness was evaluated for the typical working conditions of the dimension saws. The sawdust for analysis was obtained during the experimental longitudinal sawing of beech wood and different types of modified beech wood. The cutting process was performed using a high-efficiency thin circular G.D.A saw blade (produced by the Italian company Gianluca-Donatella-Adami) for trimming boards to size. The technical and technological conditions of sawing are presented in table 1.

Table 1. Technical and technological conditions of sawing

Parameter	Value
Diameter of saw D	350 mm
Number of teeth z	108
Tooth shape	WZ
Saw blade thickness	2.8 mm
Clearance angle α	12°
Edge angle β	68°
Rake angle γ	10°
Inclination angle of the main cutting edge l_s	15°
Cutting speed v_c	73.3 m/s
Feed speed v_f	9 m/min
Chip thickness h_m	0.013 mm
Distance between the table and the saw axis a_e	125 mm
Momentary number of cutting teeth	3

Native Beech wood is not suitable for outdoor application or moisture-sensitive areas, because of its poor natural durability and dimensional stability. Therefore, modified beech wood products, which reduce these disadvantages, have been developed [Bollmus et al. 2009].

Bendywood – this is a solid hardwood that can be worked like normal wood and then bent in a cold and dry state. This special wood is obtained from blanks of hardwood (beech, ash, oak and maple) which has undergone a particular thermo-mechanical process. The timber is treated with steam and then, while still damp, it is compressed along approx. 20% of its length and is then clamped into a mould to that length and dried. The wood can then be easily worked using traditional methods and bent to a radius of ten times (1:10) its thickness in a cold and dry state offering great time savings, cost savings and products with a better finishing compared to traditional wood bending or laminating techniques [What is Bendywood® 2014].

DMDHEU – this modified beech wood product is based on a vacuum-pressure impregnation with DMDHEU (dimethyloldihydroxyethyleneurea) which reacts under hot steam conditions within the cell wall. It is assumed that there is a cross--linking between the hydroxyl groups of cell wall compounds with DMDHEU as well as polycondensation. Hence, durability and dimensional stability are improved and coating or gluing is possible. The mechanical properties react differently. The compression strength and hardness are increased, the bending strength and modulus of elasticity do not change significantly, and the shear strength, tensile strength and impact bending strength decrease [Bollmus et al. 2009].

Lignamon – this material is based on a compressed beech wood modified by ammonium. The technological process is composed of four basic steps. First, untreated beech wood with a high moisture content (18 ± 3%) is heated to a maximum of 103°C. Second, the sample is plasticized using ammonia steam. Then the sample is compressed within the range of 0.8 MPa to 1.3 MPa. The higher the pressure, the denser the final Lignamon sample becomes. Lignamon exhibits higher durability and density, and a darker colour. This material can be used as a substitute for imported tropical wood, alloys, and plastics. The properties of Lignamon are primarily based on the properties of raw wood material (*Fagus sylvatica* L.) and its technological processing [Pařil et al. 2014; Troppová et al. 2013].

Under precisely defined conditions, sampled dust and sawdust were exposed to grain size analysis by means of Retsch AS 200 digit apparatus on a set of sieves with mesh sizes 1 mm, 0.5 mm, 0.25 mm and 0.100 mm, respectively, during a time of T = 10 min. The weights of fractions on the sieves were determined on Vibra AJ-420-CE laboratory scales with a weighing accuracy of 0.001 g.

Sieve analysis gives only a general particle-size distribution without any information considering the mass concentration of respirable fraction of dust [Dzurenda, Orłowski 2011]. Therefore, the Analysette 22 Microtec Plus laser particle sizer was used to specify details concerning the size of the respirable particles of dust smaller than 100 μm which collected in the bottom collector. The laser particle sizer automatically carries out a particle size measurement according to a predetermined Standard Operating Procedure and theoretical assumptions. The obtained results were processed by MaScontrol software in order to generate the particle size distribution curves of the tested dust samples.

The curve of cumulative distribution $Q_r(x)$ demonstrates the total quantity of all the particles with an equivalent diameter smaller than or equal to x. Each point of this distribution represents the sum of all the particles from x_{min} to x. The curve of the density distribution $q_r(x)$ is the first derivative of $Q_r(x)$ by x. It is frequently a bell shaped curve.

In agreement with $dQ_r(x) = q_r(X)\,dx$, $q_r(x)$ is the component of a quantity $dQ_r(X)$, which is contained in the interval dx for particles from x and $x + dx$. It follows a random quantity r (when $r = 3$, it means volume distribution), where [MaScontrol 2009]:

$$q_r(x) = \frac{x^r \cdot q_0(x)}{\sum_{i=1}^{n} x_i^r \cdot q_{0i}(x_i)} = \frac{dQ_r(x)}{dx} \tag{1}$$

Results and discussion

Table 2 presents the results of the granulometric composition of dry sawdust which were created during cutting of native beech and modified beech samples. The results were obtained by the method of sieving. This overall interpretation of particle-size distribution provides preliminary and general information about the sawdust. The highest gravimetric proportion occurred at an interval of 0.100 mm to 0.250 mm except in the cutting of the DMDHEU. The highest gravimetric proportion of modified beech DMDHEU was in the particles which were smaller than 0.100 mm. The percentage of occurrence of the particles was relatively high and in terms of occupational health and safety, they are the most dangerous for workers in the woodworking environment.

Table 2. Particle size distribution of dust particles

Particle size [mm]	Mass share [%]			
	Lignamon	DMDHEU	Bendywood	beech
<0.1	15.77	73.13	20.48	16.36
0.1–0.25	62.56	25.81	47.78	51.69
0.25–0.5	20.75	0.50	22.47	26.30
0.5–1.0	0.82	0.40	8.03	4.89
>1.0	0.10	0.16	1.24	0.76

Fig. 2 presents the granularity plots of sawdust obtained during the sawing of different modified beech samples and native beech wood ranging from 100 μm to 1 mm. The cumulative remainder of the fraction and also the results obtained from the sieve analysis prove that the sawdust created during the cutting of the DMDHEU was finer than the sawdust from native beech and other modified materials. This fact can be attributed to the increased fragility of this modified beech wood. In contrast to native beech, chemically impregnated and compressed DMDHEU beech is of greater hardness, but, on the other hand, it is a fragile material. Shear stress and tensile strength are reduced, which substantially influences the creation of fine sawdust [Bollmus et al. 2009]. It was also noticed that the dust created during the cutting of Bendywood was finer than when machining the native beech and Lignamon. There was an increase in the share of fine fraction in the range of granularity x < 100 µm at the expense of the fraction x = 0.25–1 mm. Bendywood is known as a material with higher density and very good bending properties. Therefore, a higher content of finer sawdust can be explained by the characteristic features of the inner structure which include micro-cracks on the walls of the libriform fibres and chemical changes in the lignin-carbohydrates matrix. A slight waviness of the fibres, created as a reflection of the longitudinal compression load, also had a positive effect on producing finer sawdust in the sawing process. The properties of Lignamon are primarily based on the properties of raw wood material, therefore this modified material had a similar cumulative particle-size distribution to native beech dust.

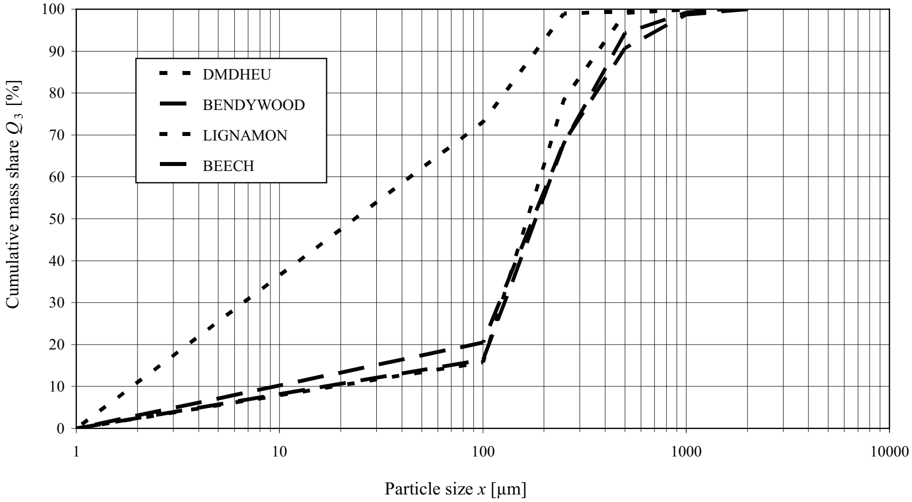

Fig. 2. Cumulative particle-size distribution

Fig. 3 shows the results of the analysis of dust taken from the bottom collector of the sieving machine which were generated by MaScontrol software on analysing the measuring data from the particle sizer. For the graphic representation, the overall data is arranged according to the geometric dimension of the particle (for example, the equivalent diameter) and plotted on the x-axis of a coordinate system. The components that are associated with the size of the individual elements and indicate the shares of individual particles within the overall distribution are depicted along the y-axis.

These results indicate that the content of ultrafine particles in the tested dust created during the cutting of the modified DMDHEU beech was higher than in the case of the other samples. The particle-size distribution obtained by the particle measurement method with laser diffraction gave a different range of the most numerous particles. It can be seen that the dust particles with a size below 100 µm constituted about 50% (for Bendywood, Lignamon and native beech) and about 75% (for DMDHEU) of the total analysed material. This demonstrates the uncertain limits of both methods due to the specific shape of the wood dust particles. The length of the particles is usually greater than their thickness and width and this fact may be the reason why the wood dust particles pass through a smaller size of sieve mesh than their length.

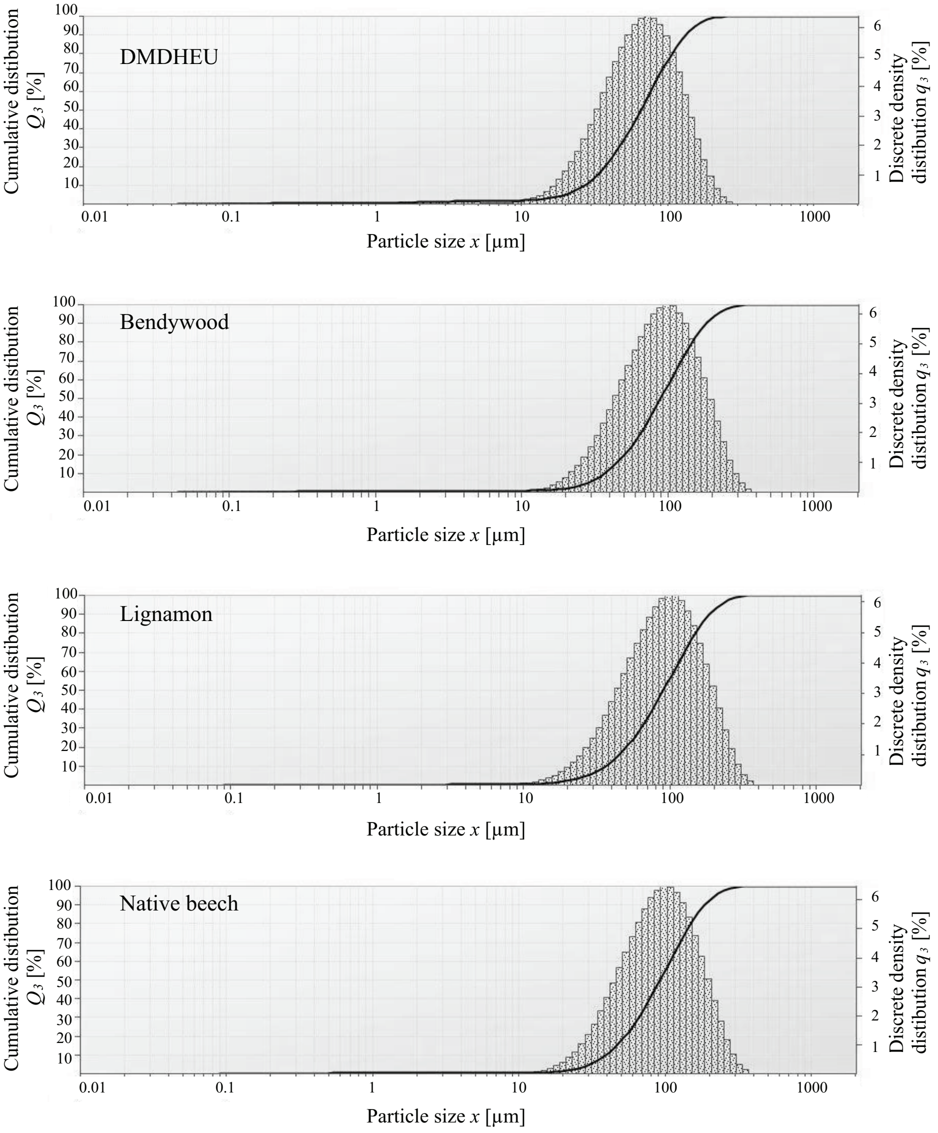

Fig. 3. Particle-size distribution of dust created during the sawing of beech wood and its modifications obtained by laser particle measurement

On the plots, two types of quantities can be seen:

- the cumulative distribution Q_3,
- the density distribution q_3.

These empirical functions of the particle size distribution of the tested dusts measured by the laser particle sizer are the source of statistical data (table 3). Additional information on the particle size distribution which may be useful to its evaluation can be derived from these data.

Table 3. Statistical values

Material	Arithmetic mean	Modal value	Median value
	[µm]		
DMDHEU	73.3	72.4	65.1
Bendywood	100.8	100.1	88.9
Lignamon	103.4	104.2	92.3
Native beech	103.6	100.1	91.7

On the basis of the particle-size distribution obtained by the laser diffraction method, the fractions of dust were calculated (in the most important ranges <2.5 µm, 2.5–4 µm, 4–10 µm, 10–20 µm and further). The content of the fractions of dry sawdust from the unmodified beech and modified beech samples in the total mass of dust is presented in table 4 and in table 5.

Table 4. Mass rate of the smallest particles

Upper limit [µm]	Mass rate in the smallest fraction from the sieving [%]			
	DMDHEU	Bendywood	Lignamon	native beech
2.5	1.10	0.52	0.25	0.41
4	1.49	0.65	0.31	0.46
10	1.96	0.81	0.56	0.50
20	5.09	2.02	2.27	1.35
30	12.74	5.96	6.44	4.72
40	23.07	12.19	12.62	10.47
50	34.12	19.68	19.92	17.66
60	44.81	27.71	27.70	25.54
70	54.57	35.74	35.51	33.55
80	63.11	43.47	43.04	41.35
90	70.49	50.74	50.15	48.75
100	76.69	57.42	56.72	55.58

Table 5. Mass rate in the total dust

Upper limit [μm]	Mass rate in the total dust [%]			
	DMDHEUr	Bendywood	Lignamon	native beech
2.5	0.802	0.106	0.039	0.067
4	1.087	0.134	0.050	0.075
10	1.433	0.166	0.088	0.081
20	3.723	0.413	0.357	0.221
30	9.313	1.221	1.016	0.772
40	16.870	2.497	1.990	1.713
50	24.955	4.032	3.140	2.889
60	32.766	5.676	4.368	4.178
70	39.906	7.321	5.598	5.489
80	46.150	8.904	6.786	6.765
90	51.549	10.395	7.908	7.974
100	56.082	11.762	8.943	9.092

It should be noted that the occurrence of particles with a size lower than 10 μm, expressed by distribution function Q_r, was only about 1.4% for the chemically treated DMDHEU beech, about 0.17% for the hydro-thermally treated and compressed Bendywood beech, and about 0.08% for the native beech and compressed and ammonium treated beech Lignamon. The occurrence of these particles which pose the risk of occupational diseases is generally negligible, but it is a large amount of dust, which might pollute a huge volume of air at the acceptable limit of dust concentration during a work shift

Such fine particles were not created in the sawing conditions on the narrow-kerf frame sawing machine. Dzurenda and Orłowski [2011] observed sawdust particles ranging from 33.5 μm to 9.9 mm in the sawing of modified ash wood, and from 35.6 μm to 13.8 mm in the sawing of native ash at a feed speed in the range of 0.36–1.67 $\mathrm{m \cdot min^{-1}}$. Dzurenda et al. [2010] found that the sawdust created at the same feed speed during the sawing of thermally modified oak wood contained particles ranging from 41.2 μm to 3.6 mm and the sawdust from unmodified oak wood contained particles from 44.8 μm to 12.1 mm. These authors, as well as Dolny et al. [2009] and Barcík, Gašparík [2014], have stated that the tooling of modified wood in different conditions is a source of finer dust particles. A similar relationship has been found in this work on the sawing process with a circular saw of 3 modifications of beech wood. Their sawdust is finer than sawdust from native beech wood except Lignamon, which differs little from the sawdust of unmodified beech. This especially concerns the finest particles which can be respirable when dispersed in the air.

Conclusion

Based on the analysis carried out, it can be concluded that the sawdust from the chemically treated DMDHEU beech produced during the sawing process with the circular saw blade is finer with a distinctly larger share of the fraction in the granularity range x = 100–250 µm. Finer dust can be attributed to changes in wood structure which becomes more brittle. The differences between the native beech dust and modified material Lignamon dust are comparatively small.

Although based on the tests carried out a seemingly insignificant amount of dust of the size of 10 µm and smaller was found, it leads us to the assumption that the process of machining modified materials can be included in the technological processes which pollute the working environment. A higher content of fine dust particles poses a risk to the health of workers employed at woodworking stations. If the suction systems are inefficient, the permissible exposition limits to airborne dust in the working environment may be exceeded. If the suction device is sufficiently dimensioned and covers show the optimum shape, then it is possible to reduce the airborne dust concentration.

The sieving method is widely used to determine the particle-size distribution of wood dust [Očkajová et al. 2010]. But determining the content of fine dust particles required the simultaneous application of two methods due to the large dimensional range of the tested particles. The dust created during the sawing of beech wood modifications contains both the very fine fraction and large particles which often fall outside the measuring range of a laser particle sizer. Therefore determing the particle-size distribution of such a dust required the use of the simple sieving method and the advanced laser diffraction method [Rogoziński, Očkajová 2013].

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What is Bendywood®: www.bendywood.info [accessed 15.6.2014]

List of standards

ČSN ISO 9096:1998 Stacionární zdroje emisí – Stanovení hmotnostní koncentrace a hmotnostního toku tuhých částic v potrubí – Manuální gravimetrická metoda (Stationary source emissions – Determination of concentration and mass flow rate of particulate matter in gas-carrying ducts – Manual gravimetric method)

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