

Quantifying the Finest Particles in Dust Fractions Created During the Sanding of Untreated and Thermally Modified Beech Wood

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This article deals with the fractionation of wood dust by sieve after sanding. Dust from untreated beechwood was compared to dust from thermally modified beechwood (at 200 °C for 3 h). The authors hypothesized that the thermal modification changes the particle size distributions of the dust sieve fractions and that all the dust sieve fractions contain the finest particles, which are suspendable in the air and are potentially respirable. To obtain dust for testing, both wood materials were sanded with P120 paper at a belt speed of 14.5 m/s and a pressure of 0.65 N/cm². A set of sieves with aperture sizes of 25, 80, and 250 µm were used to separate the dust into sieve fractions with grain sizes less than 25 µm, 25 to 80 µm, 80 to 250 µm, and greater than 250 µm. The content of the finest particles in the fractions was measured *via* a laser particle sizer. Both dusts had similar particle size distributions. In addition, each investigated fraction of both dusts contained the finest particles, *i.e.*, less than 10 µm. It follows that the laser analysis method may be necessary to correctly assess the occupational risk at a sanding.

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INTRODUCTION

Heat treatment is a process for changing the physical properties of wood and the appearance of its surface (Olek *et al.* 2013; Pelaez-Samaniego *et al.* 2013). Thermally modified wood has reduced volumetric mass density, changed hygroscopicity and flammability, increased biological resistance, and improved dimensional stability (Osvaldová and Osvald 2013; Gašparík *et al.* 2017; Čermák *et al.* 2021; Makovicka Osvaldova *et al.* 2020). Furthermore, woodworking energy consumption is advantageously

reduced (Kubš *et al.* 2016). However, some strength properties are deteriorated, making the wood more fragile (Blokland *et al.* 2020). Gluing thermally modified wood is usually more difficult than gluing untreated wood (Vidholdová *et al.* 2021). In addition, due to changes in the chemical structure resulting from the effects of elevated temperatures, the wood acquires a darker color, which makes it more attractive (Dudiak 2021). During the heat treatment of wood, no chemicals are used, so it is not toxic and does not pose a threat to the environment. Non-toxicity, improved properties, and a more attractive appearance are the primary reasons for the increased use of thermally treated wood (Candelier and Dibdiakova 2021).

Wood dust, which creates atmospheric particulate matter, is dangerous to human health (Pędzik *et al.* 2020). Particles resulting from the woodworking of thermally modified wood may have different properties from particles made from untreated wood. These wood particles may be finer and therefore more susceptible to being airborne for a longer period of time, as well as being a respirable fraction, possibly posing a serious threat to human health.

Kučerka and Očkajová (2018) studied the properties of the dust created during the sanding of thermally modified wood from sessile oak (*Quercus petraea*) and Norway spruce (*Picea abies*). The test results showed that the lowest values of the dust fraction, with a size of less than or equal to 0.08 mm, were obtained at a processing temperature of 220 °C for both species. In the case of oak, the highest amounts of dust were obtained from the 32 µm fraction. The authors stated that the increase in the treatment temperature did not affect the amount of dust generated. The authors explained that the high amount of dust created during sanding was due to the decreased wood density resulting from the increased temperature during the modification process.

Očkajová *et al.* (2019) examined the relationship between the density of three species of wood, *i.e.* sessile oak (*Quercus petraea*), Norway spruce (*Picea abies*), and Meranti (*Shorea acuminata*), subjected to thermal modification and the amount of dust created as a result of sanding the wood. The amount of thermally modified oak dust particles that were less than or equal to 80 µm was similar to the amount of untreated wood at 92% to 95%. A considerable decrease in the amount of these particles was recorded only at 220 °C. The largest amount of dust with a size less than or equal to 80 µm for other species was determined at a temperature of 160 °C and decreased as the modification temperature increased (approximately 87% for meranti and 93% for spruce). Therefore, the increase in temperature reduced the amount of wood dust particles formed when sanding spruce, oak, and meranti wood, separated in the smallest sieve (32 µm) and at the bottom of the screening machine, and increased the number of larger particles. The results of the granular analysis were similar, primarily due to the decreased density of the thermally modified wood, which confirmed the results of the previous research (Hlásková *et al.* 2018).

Očkajová *et al.* (2020b) subjected the thermally modified oak and pine wood dust generated during longitudinal milling with a ZDS-2 spindle milling machine to a granulometric analysis. In the case of both tested wood species, it was observed that the higher the modification temperature, the greater the amount of small-sized dust particles. This relationship was compared to dust from the sanding process, and the analysis of the residue curves showed that this relationship was inverse. Residue curves for the sanding dust were shifted toward the particles with a smaller amount in the dust fractions as the wood modification temperature increased for both species. The largest share of the fine fraction, *i.e.*, less than or equal to 80 µm, was recorded for spruce (84% to 93%). Also

based on previous studies on oak sanding dust, it can be concluded that the fraction amounts with a particle size less than or equal to 80 μm was high when sanding various wood species and ranged between 85% and 95% (Marková *et al.* 2016; Očkajová *et al.* 2018).

Očkajová *et al.* (2020a) studied the particle size distribution of thermally modified spruce and oak wood particles formed during longitudinal milling on a ZDS-2 low-spindle milling machine. The authors stated that the amount of coarse, fine, and very fine dust fractions increased as the wood modification temperature increased. Furthermore, the amount of particularly hazardous dust, *that is*, less than or equal to 80 μm , increased in oak, but only occurred in spruce after applying a considerably increased temperature, *that is*, 200 °C and 220 °C. Particles less than or equal to 32 μm were obtained in very small quantities.

The analysis performed by Kminiak and Dzurenda (2019) showed that more than two thirds of the maple (*Acer pseudoplatanus* L.) wood particles produced during milling on a 5-axis CNC machining center were coarse-grained fractions, *i.e.*, greater than 100 μm . The amount of particles with a size smaller than 125 μm did not exceed 2.5%. The milling of thermally treated maple wood did not form the finest dust fraction, which meant that it would not have a negative impact on the environment or human health. The results obtained did not confirm the thesis suggested by the earlier authors that changes that cause an increased amount of fine dust fraction occur as a result of the heat treatment on the chemical structure of wood.

The results of research by various authors suggest that thermal modification contributes to the reduction of the dust fraction from milling and sawing with a particle size less than or equal to 80 μm (Dzurenda *et al.* 2010; Očkajová *et al.* 2020a; Očkajová *et al.* 2020b). However, in scientific publications on the dust generated during sanding thermally modified wood (oak, spruce, meranti), based on the sieve analysis performed, a lower content of particles with the smallest size was found in the dust from the wood modified at the highest temperature (220 °C) (Kučerka and Očkajová 2018; Očkajová *et al.* 2019). The absence of the finest particles, that is less than 32 μm , was also found by Kminiak and Dzurenda (2019).

Such statements are in contradiction with the research results described by Hlaskova *et al.* (2018). These authors, based on the results of the sieve analysis, found that the increased modification temperature of beech wood resulted in a reduced content of the smallest particles in the dust resulting from sanding. However, in the dust from wood modified at higher temperatures, the microscopic image analysis showed a much higher finest particle content. The use of the laser diffraction analysis method to assess the finest particle content in the under-sieve fraction (containing the smallest particles) also allowed the conclusion that when modified pine wood was milled, the modification temperature influenced the finest particle content in the resulting dust, causing it to increase (Piernik *et al.* 2019).

The occurrence of the smallest particles suspended in the air was also investigated. Such particles, with dimensions smaller than 10 μm , were found during the sawing of and unmodified and thermally modified aspen, fir, maple, ash, and poplar. The thermal modification of wood did not affect the amount of these particles in the air (Aro *et al.* 2019).

As is well known, the sieving method has limitations, as its accuracy decreases with particles smaller than 100 μm , with a mixture of particles of different specific weights, with a mixture of particles prone to agglomeration, *e.g.*, with increased moisture content, when containing resin or adhesive, or susceptible to triboelectric charging, with non-

spherical particles, *e.g.*, of elongated shape, or with brittle particles.

The purpose of this research was to characterize the dust fractions generated from sanding untreated and thermally modified beech wood and determine the finest dust particle content with sizes less than 10 µm in all dust fractions, separated by sieve analysis using the laser diffraction method.

EXPERIMENTAL

Materials

European beech (*Fagus sylvatica* L.) wood was selected as a test material. The wood heat treatment included the following: an initial phase in moist air followed by heating in superheated steam after the temperature reached 130 °C, a maximum heating phase (at a temperature of 200 °C for 3 h), and a cooling phase with superheated steam followed by cooling in moist air only. The thermal modification method was consistent with the method described in the ThermoWood® Handbook (ThermoWood 2021). The wood dust was created with a small belt sander (Cormak, Siedlce, Poland) with a horizontal abrasive belt arrangement and P120 sandpaper with dimensions of 1000 mm × 80 mm. A belt speed of 14.5 m/s and a pressure of 0.65 N/cm² were applied. The wood sanding parameters were identical to those in earlier publications (Pędzik *et al.* 2020; Sydor *et al.* 2021; Pędzik *et al.* 2021). Planks with a width equal to the width of the belt were used. The dust generated during sanding was collected using a large polyethylene bag (so all dust was collected, *i.e.* settled dust and airborne dust).

Methods

The particle size analysis and the calculation of the fine dust particle content were performed using the methods described by Hlásková *et al.* (2015), Rogoziński *et al.* (2015), and Piernik *et al.* (2019). Sieve analysis was performed using a laboratory sieving machine (AS 200, Retsch, Germany) with a set of sieves with apertures of 25 µm, 80 µm, and 250 µm (the sieve apertures were successively three times larger than each other). As a result of the sieve analysis, four dust fractions were obtained: less than 25 µm, 25 to 80 µm, 80 to 250 µm, and greater than 250 µm. The size fraction less than 25 µm was the smallest sieve fraction, the 25-80 µm fraction contained particles that passed through an 80 µm aperture size sieve but were retained by a 25 µm sieve, the 80-250 µm fraction contained particles sieved through a 250 µm sieve but retained by an 80 µm sieve, and the fraction greater than 250 µm were particles retained by a 250 µm sieve. The mean arithmetic particle sizes were calculated according to Eq. 1,

$$\bar{x} = \sum_{i=1}^n x_i \cdot q_{3i} \quad (1)$$

where q_3 is the particle distribution by mass, x is the mean value of the particle size class, and n is the number of particle classes.

Three sieve fractions were taken for verification of the finest particle content: less than 25 µm, 25 to 80 µm, and 80 to 250 µm. The greater than 250 µm fraction was not tested, because it contained particles larger than 2000 µm, which are outside of the measuring range of the laser particle sizer. The finest particle contents, *i.e.*, with sizes less than 2.5 µm, less than 4 µm, and less than 10 µm, were measured using an Analysette 22 Microtec Plus laser particle sizer (Fritsch, Germany). This instrument measures the length-related equivalent diameters of dust particles. Particles of this size can easily suspend in

the air and are then can be inhaled and therefore by dangerous to human health (Beljo-Lučić *et al.* 2011).

Statistical Analysis

A multivariate analysis of variance (ANOVA) was performed to test whether thermal modification (a), sieve aperture size (b), or particle size (c) had an effect on the finest particle content in the dust sieve fraction from beech wood. The post hoc HSD Tukey test was used to test the significance of differences between the average particle size of the dust from untreated (control) and thermally modified beech wood as well as the content of less than 2.5 μm , less than 4 μm , and less than 10 μm dust particles in the dust fractions of the sieve. Significance was established with a p-value of less than 0.05. The statistical significance of the differences in the average content of the smallest particles in the tested fractions of the two types of dust (untreated and thermally modified beech wood) was shown with superscripts a and b. Identical superscripts represent non-significant differences between the analyzed values. The experimental data was statistically analyzed using STATISTICA 13.3 software (TIBCO Software Inc., Palo Alto, CA).

RESULTS AND DISCUSSION

Sieve Analysis Results

The results of the dust fractionation *via* sieve analysis for the two tested wood materials are presented in Fig. 1. The comparison of the fraction masses showed that the dust produced from the unmodified wood had a structure similar in size to that of the thermally modified wood dust. The mass of the 25 to 80 μm fraction, calculated by Eq. 1, was 31.5% of the mass of the untreated wood dust, while for modified wood dust, the mass was slightly higher (38.4%). However, the 80 to 250 μm fraction represented 57.2% (dust from unmodified wood) and 51.7% (thermally modified wood) of the mass, respectively. Moreover, dust from thermally modified wood had a slightly higher mass fraction of <25 μm (6.6%) compared to the dust generated during sanding modified wood (6.1%). The mean arithmetic particle size, calculated by Eq. 1, was 58.14 μm for unmodified wood dust and 58.17 μm for modified wood dust. Therefore, the use of sieve analysis with this particular set of sieves did not allow the determine the difference in the average dimensions of the dust particles formed during the sanding of the untreated and thermally modified beech wood.

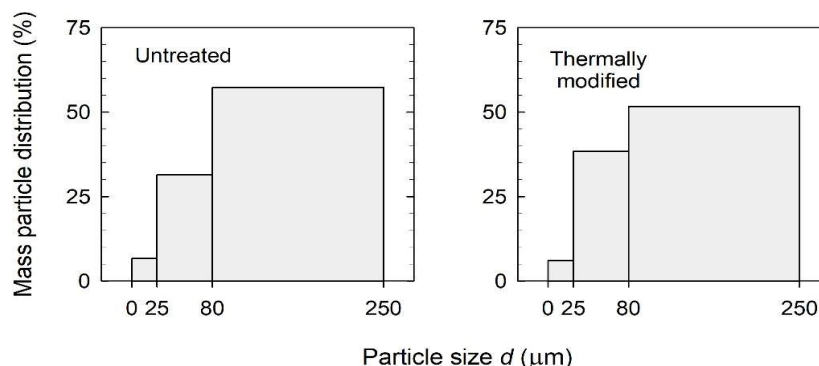


Fig. 1. Particle size distribution of the untreated and thermally modified beech wood dust *via* the sieve analysis method

Laser Analysis Results

A comparison of the cumulative and frequency distributions of the untreated and thermally modified beech wood dust, measured by laser diffraction analysis, is presented in Fig. 2. The finest particles (smaller than the aperture size) were found in the 25 to 80 μm , and 80 to 250 μm sieve fractions. Particles with dimensions smaller than 10 μm , smaller than 4 μm , and even smaller than 2.5 μm were found. They were identified in the three dust fractions analyzed previously separated by the sieve method (as shown in Fig. 2). This demonstrates that the use of the laser analysis method is valuable to correctly assess the level of occupational risk at a workstation equipped with a wood sander.

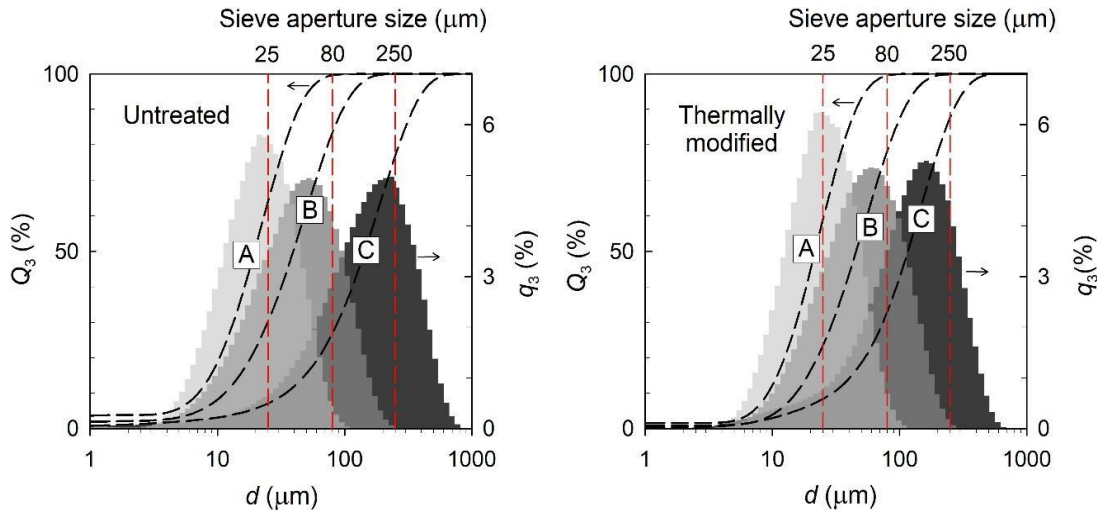


Fig. 2. Cumulative particle size distribution (Q_3) and particles frequency distribution (q_3) of the untreated and thermally modified beech wood dust fractions: A is less than 25 μm ; B is 25 μm to 80 μm ; and C is 80 to 250 μm (Note: Red dashed line is the sieve aperture size)

The Results of the Variance Analysis

The results of the variance analysis (ANOVA) for the particle size distribution of the untreated and thermally modified beech wood dust are presented in Table 1.

Table 1. Analysis of Variance (ANOVA) for the Particle Size Distribution of the Untreated and Thermally Modified Beech Wood Dust with Regards to the Effects of the Heat Treatment, Sieve Aperture Size, and Particle Size

Effect	SS	df	MS	F-value	p-value
Intercept	137.39	1	137.39	173.92	0.0000
Heat treatment (a)	0.72	1	0.72	0.92	0.3418
Sieve aperture size (b)	65.05	2	32.52	41.17	0.0000
Particle size (c)	174.06	2	87.03	110.16	0.0000
a × b	0.65	2	0.33	0.41	0.6629
a × c	1.70	2	0.85	1.07	0.3473
b × c	98.14	4	24.54	31.06	0.0000
a × b × c	1.10	4	0.27	0.35	0.8452
Error	52.14	66	0.79	-	-

Note: SS is the sum of squares; df is the degrees of freedom; MS is the mean squares; and F is the Fisher's F-test

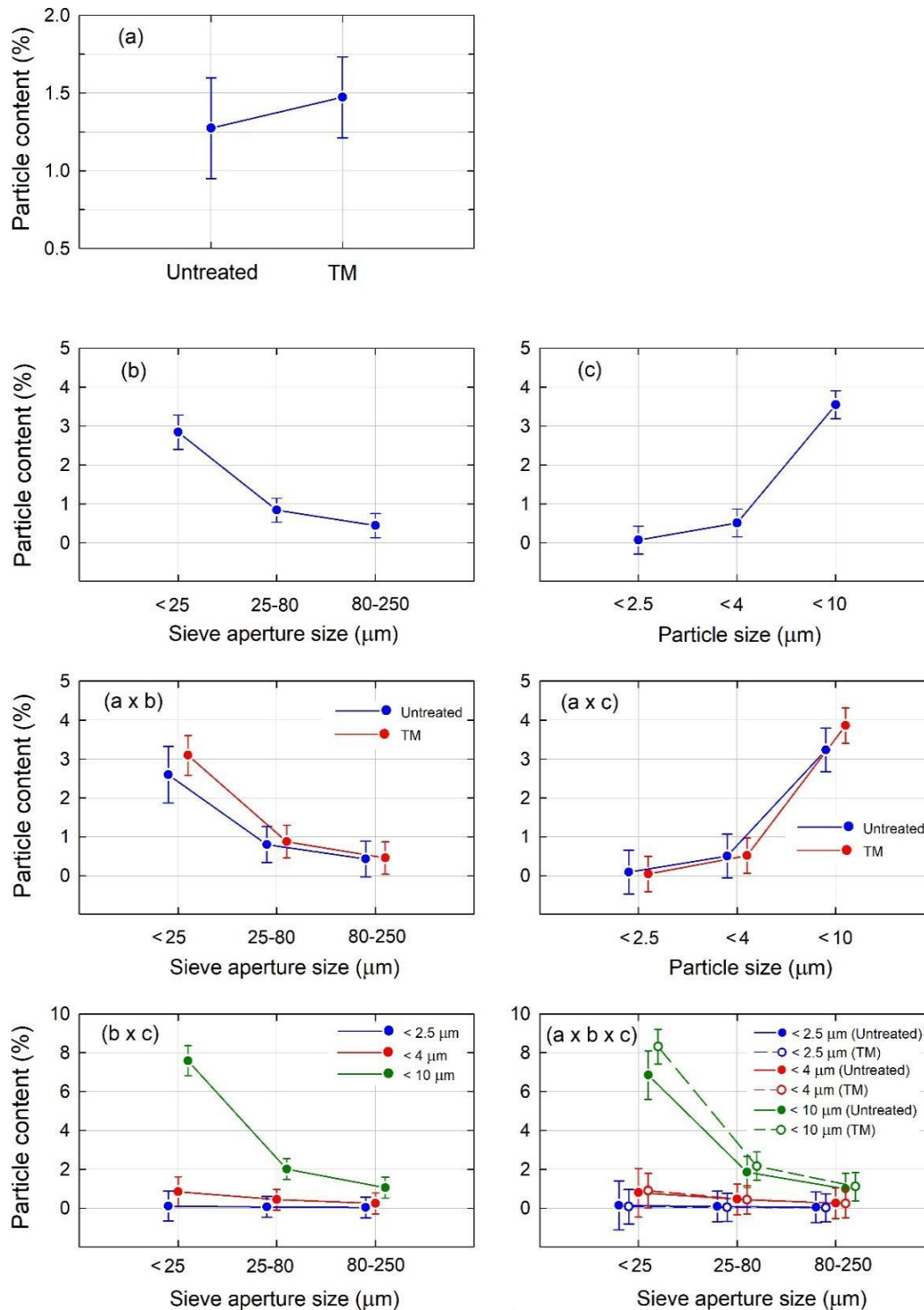


Fig. 3. Graphic illustration of the results of the analysis of variance: a) heat treatment; b) aperture size of the sieve; and c) particle size (note: error bars depicted \pm 95% confidence limits)

The results of the variance analysis confirmed the nonsignificant influence of the heat treatment (a) on the content of the finest, potentially respirable particles in the corresponding fractions of both tested beechwood dust samples (for p-value is less than 0.05). The content of the finest dust particles, *i.e.*, smaller than 2.5, 4, and 10 μm ,

significantly depended (for p-value is less than 0.05) on other factors included in the analysis, *i.e.*, the size of the sieve aperture (b) and the size of the particles (c). Moreover, the results of the variance analysis confirmed the existence of a strong interaction of factors (b) and (c), *i.e.*, the size of the sieve aperture and the size of the particles. A graphical representation of the performed analysis of variance is shown in Fig. 3.

Table 2 shows the experimental data and the results of the direct comparisons (Tukey's HSD test) of the average content of the finest, potentially respirable, particles in the untreated and thermally modified beech wood dust fractions. All investigated fractions of the two tested types of wood dust had a different finest particles content. The average proportion of particles smaller than 2.5, 4, and 10 μm in all tested dust fractions was within the following ranges: 0.02% to 0.14%, 0.23% to 0.89%, and 0.99% to 8.31%, respectively.

The untreated wood dust contained approximately twice the amount of finest particles (less than 2.5 μm) compared to the thermally modified wood dust. This result was recorded for each of the three tested dust fractions (less than 25 μm , 25 to 80 μm , and 80 to 250 μm). In contrast, untreated wood dust had a lower average particle content of less than 4 μm and 10 μm compared to the average particle content of the thermally modified wood dust. In all cases analyzed, the average content of the smallest particles (smaller than 10 μm , *i.e.*, smaller than the aperture size) was calculated. The less than 25 μm and 80 to 250 μm fractions of both tested dusts had the highest and lowest amounts of the finest particles, respectively.

Table 2. Average Values of the Fine Particle Content (%) of the Untreated and Thermally Modified Beech Wood Dusts with Regards to the Sieve Aperture Size and Particle Size

Treatment Option	Sieve Aperture Aize (μm)	< 2.5 μm	< 4 μm	< 10 μm
Untreated	< 25	0.14 ^a \pm 0.08	0.80 ^a \pm 0.49	6.85 ^b \pm 5.44
	25 to 80	0.09 ^a \pm 0.04	0.46 ^a \pm 0.01	1.86 ^{ab} \pm 1.21
	80 to 250	0.04 ^a \pm 0.01	0.25 ^a \pm 0.08	0.99 ^a \pm 0.45
Thermally modified	< 25	0.07 ^c \pm 0.01	0.89 ^b \pm 0.17	8.31 ^b \pm 2.05
	25 to 80	0.04 ^b \pm 0.00	0.42 ^a \pm 0.14	2.16 ^a \pm 0.36
	80 to 250	0.02 ^a \pm 0.00	0.23 ^a \pm 0.07	1.11 ^a \pm 0.52

Note: Mean value (n = 6) \pm standard deviation; identical superscripts (a, b, c) do not indicate a significant difference (p-value less than 0.05) between mean values according to the post hoc Tukey's HSD post hoc test

The results of the post-hoc Tukey's (HSD) test for the finest particle content for the investigated fractions of both dust types are presented in Fig. 4. The significance of the differences in the average of the finest particle content values in the individual analyzed dust fractions was denoted using superscripts a and b. Identical superscripts represent non-significant differences between the analyzed values.

In most of the analyzed cases, it was confirmed that there was a non-significant difference in the average content of the finest particles in the fractions of dust from the untreated wood and thermally modified wood samples (for p-value equals 0.05). A statistically significant difference in the average fine particle contents for the untreated and thermally modified dusts was confirmed only for particles less than 2.5 μm occurring in the 25 to 80 μm and 80 to 250 μm fractions (as shown in Fig. 4).

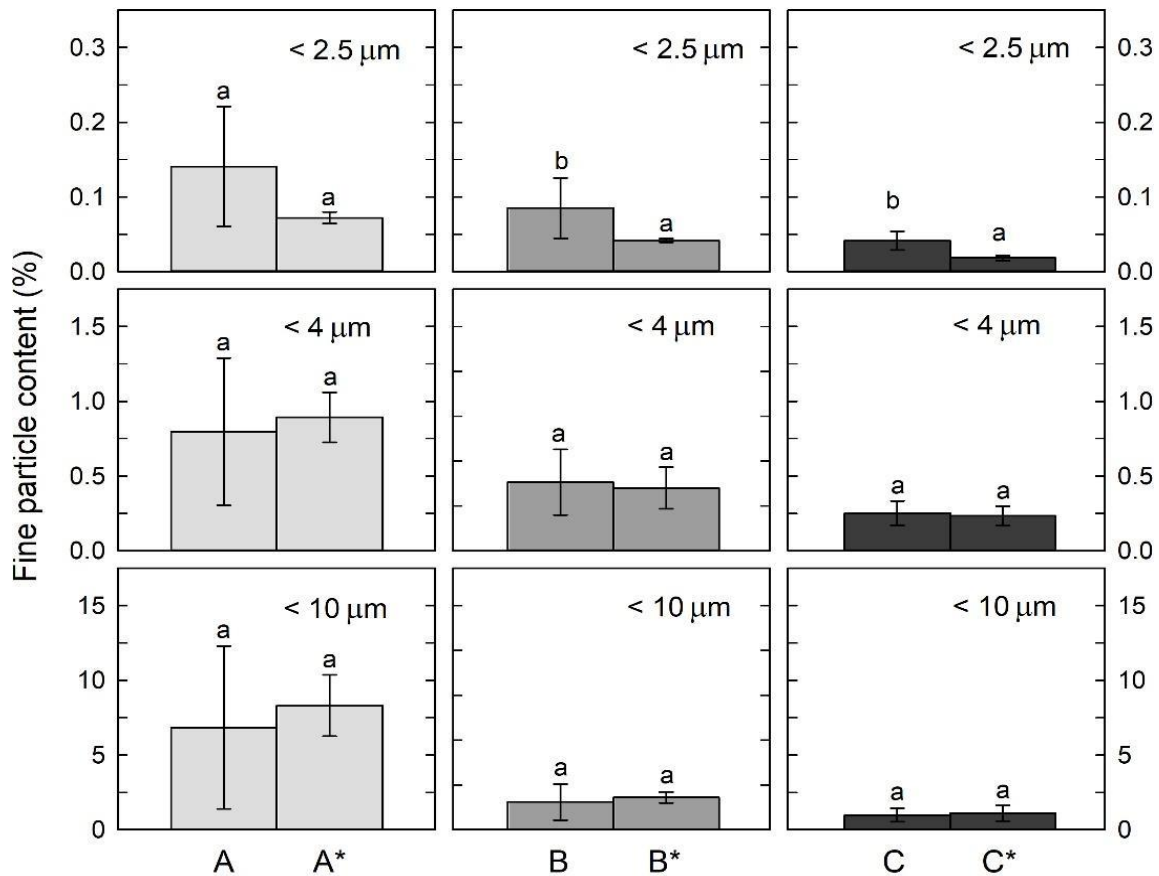


Fig. 4. Comparison of the average content of the finest particles in the untreated and thermally modified beech wood dust fractions: A) fraction less than 25 μm; B) fraction 25 μm to 80 μm; and C) fraction 80 μm to 250 μm (Note: * indicates the fraction of thermally modified wood; identical superscripts (a and b) denote no significant differences for a p-value is less than 0.05; $n = 6$; and error bars depicted \pm standard deviation)

Discussion

As it is known in the case of wood dusts, the concern of industrial hygienists is more for the carcinogenic coarse particles exposure than for the fine particles exposure. Therefore this research is the study with respect to the physical properties and mechanisms of wood dusts generation but not health hazard study by wood dust. The results of this study showed that it is not possible to completely separate the individual dust fractions using a set of sieves. In the 25 to 80 μm and 80 to 250 μm fractions (retained on the 25 μm and 80 μm sieves) there were also particles with a particle size less than 10 μm. For this reason, the sieve analysis method can only be used for a preliminary assessment of the dust dimensional structure. The content of the smallest particles which, after dispersion in the air, can penetrate the human respiratory tract, should be determined by other methods. Therefore, in the described research, the laser diffraction analysis method was used in addition to the sieve method, which allowed the presence of particles with a particle size of less than 2.5 μm, less than 4 μm, and less than 10 μm to be confirmed in all sieve fractions of the two types of wood dust tested.

This was the first attempt to measure the content of very fine particles in the wood dust from thermally modified wood. So far, in assessing the content of the finest particles, only the under-sieve fraction (with particles penetrating the finest sieve) had been used, if

at all, considering that it is only this fraction that contains the finest particles. The under-sieve fraction contains most of the smallest particles (Fig. 4), but their content in the sieve fractions retained on sieves with a larger aperture size cannot be ignored in the dust assessment, especially from an occupational point of view.

Two scientific papers are examples of recent sawdust tests using only sieve analysis. Kminiak *et al.* (2020), when examining unmodified and modified birch wood dust resulting from frame sawing and CNC milling, failed to detect the presence of potentially respirable fine dust in the under-screen fraction (aperture size less than 32 μm). Kminiak *et al.* (2021) compared the fine dust content in the treatment of wood and medium-density fiberboard (MDF). They used the finest sieve (32 μm in size) and found the presence of the finest particles in the under-sieve fraction; with a lower content in spruce, oak, and beech wood and a higher content in MDF. The results of this study indicated that if the cited authors had additionally used the laser diffraction method, they could have confirmed the presence of the finest dust.

Dzurenda *et al.* (2010) studied the effect of thermal modification on the particle size of oak wood. The dust was obtained during sawing with a feed speed v_1 of 0.36 $\text{m}\cdot\text{min}^{-1}$ and v_2 of 1.67 $\text{m}\cdot\text{min}^{-1}$. A set of sieves with the following mesh sizes was used for sawdust fractionation: 2000, 100, 500, 250, 125, 80, 63, and 32 μm . The authors found that the thermally modified oak sawdust was finer. The largest content (approximately 89.36%) was determined in the fraction obtained after sieving through the 125 to 500 μm sized sieves. The fraction from sieves with a size less than or equal to 80 μm was less than 5%, and no fraction was observed from the sieve with a size less than 32 μm . Contrary to the results of the cited authors, the results of this study did not show differences in the dimensions of the particles of both types of dust (Fig. 1). However, this may lead to the conclusion that thermal modification does not affect the degree of sanding waste after sanding and the content of the finest particles in it or that both methods used in this study did not allow such differences to be found. This shows that the use of the common sieve analysis method to assess the occupational health risk of dusts generated during wood processing is not sufficient. Therefore, further research on this problem should be carried out in order to finally exclude or confirm the influence of the thermal modification of wood on the dimensions of dust with the use of other methods.

Based on the results obtained, it was found that there were no statistical differences in the masses of the size fractions between the dust from the unmodified beech wood and the dust from the thermally modified beech wood (Fig. 1). The primary result of the research was the confirmed presence of respirable particles in each of the separated dust fractions.

Particles smaller than 2.5 μm , smaller than 4 μm , and smaller than 10 μm were identified. The presence of these particles in the fraction less than 25 μm was obvious; however, theoretically, such particles should not be present in the 25 to 80 μm and 80 to 250 μm fractions. The admixture of particles smaller than 10 μm was greater for the 25 μm to 80 μm fraction compared with the 80 μm to 250 μm fraction (Fig. 4).

CONCLUSIONS

1. The dust from the untreated and thermally modified beech wood was sieved in a similar way, and a set of sieves where the smallest aperture size was 25 μm did not allow for the proper measurement and comparison of the content of dust particles in both types

of wood dust that could be suspended in the air, forming a respirable hazardous fraction.

2. Sieve analysis alone does not completely fractionate the beechwood dust into fractions of certain sizes, *i.e.*, particles smaller than 10 μm were found in each fraction. This may be the result of the temporary combination of the finest particles with large particles due to electrostatic forces, the admixture of moisture and other caking substances, or other factors temporarily agglomerating dust particles.
3. The use of the laser diffraction analysis method may be necessary to correctly assess the level of occupational health risk in the surroundings of a workstation equipped with a wood sander.
4. The exposure to fine wood dust emissions generated from sanding both untreated and thermally modified beechwood should be regarded as a significant occupational risk to the safety and health of workers in the wood-processing industry.

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Authors' Contributions

Conceptualization, T.R.; methodology, T.R. and J.M.; validation, J.M.; formal analysis, J.M.; investigation, M.P.; resources, P.A., E.K., M.K.; data curation, J.M.; writing—original draft preparation, M.S., T.R. and J.M.; writing—review and editing, M.S.; visualization, J.M.; supervision, T.R.; project administration, J.M.; and funding acquisition, R.K. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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