Fine dust after sanding untreated and thermally modified spruce, oak, and meranti wood

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Abstract

Airborne wood dust causes health and safety hazards in the construction and furniture industry. The study verified whether the thermal modification affects the share of the finest wood dust particles (< 10 μm) created by sanding oak, spruce, and meranti wood. The experimental research included nine variants of materials (three species of wood in three states: untreated, thermally modified at 160°C, and thermally modified at 220°C). A belt sander with a dust collector allowed the collection of at least 200 g of each dust variant (P80 sandpaper and 10 m/s belt speed). Next, a set of sieves with 2000, 1000, 500, 250, and 125 μm aperture sizes was used to recognize the gradation of the wood particle aggregate. A laser particle sizer was used to determine details of dust with particle sizes smaller than 125 μm. The size distribution of the finest particles was analyzed in four fractions with particle sizes < 2.5, 2.5-4, and 4-10 μm. The results show that, surprisingly, sanding dust from thermally modified wood generates a lower average mass share of potentially harmful particle fractions than dust from untreated wood. When comparing tested wood species, it is noticed that oak dust has a higher proportion of the best particles than spruce and Meranti dust. Dust from thermally modified oak and meranti has a lower content of harmful particle fractions than dust from untreated wood. The average mass shares of these dust fractions formed during the sanding of modified wood at 160 and 220°C are not significantly different (p <0.05). The opposite was observed in the case of spruce wood because spruce dust has a low content of fine fractions, and its particles have a more irregular elongated shape. The study took into account the extreme temperatures used in the thermal modification of wood (160 and 220°C), then it can be assumed that the statements mentioned above are valid in all intermediate thermos-modification temperatures.

1 Introduction

Woodworking generates wood dust particles of various sizes and shapes. In industrial production systems, these particles are collected by local exhaust ventilation and transported through piping systems from the generation space to waste disposal units that collect this organic material as energetic and construction by-products. Unfortunately, the finest wood particles tend to become an airborne particulate matter and can harm human health by breathing in skin or eye contact. A legal limit in the United States for an employee's exposure to wood dust in the workplace is 15 mg/m³ total exposure and 5 mg/m³ exposure over an 8-hour workday. The National Institute for Occupational Safety and Health (NIOSH) has set a recommended maximum exposure level of 1 mg/m³ of exposure to total dust. Long exposure of around 1 mg/m³ to wood dust is a mucous membrane irritant and may cause dermatitis, allergic respiratory effects, mucosal and nonallergic respiratory effects, and cancer (Wood Dust and Formaldehyde, (1995)). The American Conference of Governmental Industrial Hygienists (ACGIH) recommends a 0.5 mg/m³ limit for wood species not suspected as human carcinogens. The ACGIH lists oak and beech as confirmed carcinogenic species and highlights birch, mahogany, teak, and walnut as suspected carcinogenic species. The value is below the 2 mg/m³ permissible limit (BOELV) for the inhalable fraction of hardwood dust, introduced by the European Commission (2017/2398/UE), which will be valid in the EU countries as of 18 January 2023 (a 3 mg/m³ is a permissible limit during the actual transition period). If hardwood dust is mixed with other dust types, the concentration limit value applies to all wood dust in this mixture.

The fractional composition and the amount of dust suspended in the air are not constant. The larger the particle, the heavier and faster it sinks to the ground; therefore, only dust of the smallest particles and most dangerous for humans floats in the air after a specific time. The wood dust spread into the air during woodworking contains inhalable, thoracic, and respirable fractions. An inhalable fraction consists of all particles that enter the human
respiratory tract during breathing. Inhaled airborne dust particles, not stopped into the nose, penetrate through the pharynx and the larynx and become a thoracic dust fraction (≥ 10 µm, according to WHO definition), while the finest respirable fraction (≥ 4 µm) can penetrate the lower respiratory tract (trachea, bronchus, and lungs). The sizes and shapes of wood particles spread into the air during woodworking depend on the type of woodworking, the technology parameters used, the type of processed wood material, and air relative humidity (Nasir and Cool 2020; Kminiak et al. 2020, 2021). For example, in sanding, the mean particle size of the dust created with P60 sanding paper was 1.4 times larger than that of the dust obtained with P180 granulation sanding paper (Pędzik et al. 2020). The blunt level of sanding paper is another factor affecting the particle size distribution (Sydor et al. 2021). The type of wood (hardwood or softwood) also significantly influences the particle size and the content of the dust fraction with the smallest particle sizes. The content of the particles with sizes in dust ranged from 0.21% for pine (P60 sanding paper) to 12.58% for beech (P180 sanding paper) (Pędzik et al. 2020).

Wood dust also causes other hazards. Airborne sawdust is highly explosive. The dust of the finest particles dispersed in the air at a sufficient concentration in a confined area may explode when affected by any ignition source (Callé et al. 2005; Santamaría-Herrera et al. 2023). Wood dust adversely affects the complex mechanisms of modern industrial devices. It can pollute the lubrication systems, hinders the movement of feed devices, and disables optical systems of surveillance over industrial processes (Sydor et al. 2021).

Wood dust collected during woodworking can be a raw material for industrial production. It can be admixture in making particleboard, fiberboard, and other wood-based engineering materials (Lee et al. 2022; Sydor et al. 2022). Additionally, wood dust can also be used as a fuel source in energy production (Nhuchhen et al. 2021).

The heat treatment of wood influences the particle size distribution. Heat is used in many wood technologies, for example, in the steam kiln drying of lumber, in steam wood aging, in hot-air drying of veneer, in hot-press gluing, in wood densification, in steam solid wood bending, and solid wood properties modification. An industrial-scale wood modification process by temperature was developed in 1993 in Finland (Pertti et al. 1997). In this hydrothermal processing, wood is heated for several hours at high temperatures (up to 250°C) with aqueous vapor to change its physical properties. These changes result in a reduced volumetric mass density, improved dimensional stability, and increased resistance against biological factors (Stamm and Hansen 1937). Some strength properties are deteriorated, making the wood more fragile (van Blokland et al. 2020). Particles resulting from the woodworking of thermally modified wood are generally finer compared to particles from natural wood (Majka et al., 2022). The smaller particle size of the wood dust from the wood after thermo-modification makes it more likely to make them more susceptible to dispersal in the air.

All these reasons: protection of employees' health, safety against fire, reliability of industrial equipment, the willingness to collect the entire valuable wood by-product, and changed wood properties by heat treatment, justify research and analysis of the finest wood dust fractions created during woodworking of thermally modified woods. The research described in the article aims to characterize the fine dust particles that can form a thoracic fraction when dispersed in the air, with sizes < 10 µm, generated by sanding untreated and thermally modified meranti, oak, and spruce wood. We hypothesize that the temperature of thermal modification affects the share of the fine dust particles generated during wood sanding.

2 Material And Methods

Test samples
The research program included three types of wood. Norway spruce (*Picea abies*) and Sessile oak (*Quercus petraea*) were collected in Vlčí jarok (Budča, Slovakia), at 440 m above sea level. Meranti (*Shorea acuminata*) was purchased from the sub-provider (Wood Store, Prague, Czech Republic) as originated from Malaysia. Five test samples were obtained from each type of wood. The samples were made as radial 20 × 100 × 700 mm boards cut from the logs and then dried to a residual moisture of 8%. The entire process was performed in the Research and Development Workshops of the Technical University in Zvolen (Zvolen, Slovakia).

**Heat treatment of test samples**

The samples were thermally modified in the Arboretum FLD (Czech University of Life Sciences, Prague, Czech Republic) in the Kostelec nad Černými lesy. The chamber (S400/03, LAC Ltd., Rajhrad, Czech Republic), used for thermal modification (Fig. 1a), was designed to processing the wood with ThermoWood technology. Table 1 summarizes the main parameters of the chamber used in the heat treatment of test samples.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximal temperature (°C)</td>
<td>300</td>
</tr>
<tr>
<td>Volume (l)</td>
<td>380</td>
</tr>
<tr>
<td>External dimensions, W×D×h (mm)</td>
<td>1400×1850×1200</td>
</tr>
<tr>
<td>Internal dimensions, W×D×h (mm)</td>
<td>800×800×600</td>
</tr>
<tr>
<td>Chamber weight (kg)</td>
<td>350</td>
</tr>
<tr>
<td>No. of fans</td>
<td>1</td>
</tr>
<tr>
<td>Power input (kW)</td>
<td>6.0</td>
</tr>
</tbody>
</table>

The thermal modification included two variants of temperatures, 160 and 220°C; the procedure was as follows:

1. Placing a humidity sensor, putting the samples in the chamber, setting off the thermal modification temperatures and times (values and steepness in °C/h for heating and cooling phases);
2. Thermal modification of samples in six phases: first phase – an increase of temperature to 40°C for 48 min., second phase – an increase of temperature to 130°C for 8 h and 12 min., third phase – heating to working temperature (160 or 220°C) for 3 h, fourth phase – heat treatment in working temperature for 3 h, fifth phase – cooling to 130°C and humidity treatment for 1 h and 12 min., sixth phase – cooling to 60°C with humidity treatment at the level of 4–7% for 1 h and 48 min. The process was completed when the temperature reached 60°C. Figure 1b shows the used heat treatment schedule;
3. Sample extraction from the chamber.

The used thermal modification methodology of samples has been published in the previous papers of (Kučerka and Očkajová 2018) and (Očkajová et al. 2018a).

**Dust generation by sanding**

In laboratory experiments, a narrow belt sander (JET JSG-96 (JPW Tool AG, Fällanden, Switzerland), with a belt speed of 10 m·s⁻¹, and a sanding belt (HIOLIT XO P 80, KWH Group Ltd., Vaasa, Finland) was used. Every time a new
sharp sanding belt was used for each of the nine sample variants. Figure 2 presents the laboratory sander used. Wood dust was captured using a Rowenta vacuum cleaner (Banská Bystrica, Slovakia) into Rowenta Original ZR 814 to disposable paper bags. A new paper bag was used for each of the nine sample variants. At the end of each sanding, the dust sample from a paper bag was poured into a plastic bag and hermetically closed to avoid any change in the dust parameters. Approximately 200 g of each dust sample was collected.

The wood dust particle-size distribution was tested by sieving. A standard kit of several sieves ordered vertically (2000, 1000, 500, 250, 125 µm, and the bottom collector – dust particles passed through all of the mesh screens) was placed on the vibrating stand of the sieving machine (Retsch AS 200c; Retsch GmbH, Haan, Germany) with an adjustable sieving interruption frequency (20 Hz) and a sieve deflection amplitude (2 mm/g), following STN 153105/STN ISO 3310-1 (2000) standard. As much as 30 g of material was analyzed in each sieving process. Each dust sample was exposed to six sieving processes.

The mass particle-size distribution was obtained by weighing the wood dust remaining on the sieves after sieving on the Radwag WPS 510/C/2 electronic weighing scale (Radwag Balances and Scales, Radom, Poland), with a capacity of 510 g and an accuracy of a scale with the resolution of 0.001 g. The weight figures for each sieve were recorded in MS Excel (Microsoft Corporation, Redmond, WA, USA), and the results were statistically evaluated using STATISTICA 13 software (TIBCO Software Inc., Palo Alto, CA, USA).

### Laser particle size analysis

The sieve analysis only provides information on the masses of individual fractions without any information on the particle size distribution in these dust fractions. The Analysette 22 Microtec Plus (Fritsch, Idar-Oberstein, Germany) laser particle sizer was used to specify details regarding the dust with the size of particles smaller than 125 µm (collected in the bottom collector). The laser particle sizer automatically measures a particle size according to a predetermined Standard Operating Procedure and theoretical assumptions. The obtained results were processed by MaScontrol software (Fritsch, Idar-Oberstein, Germany). It gives two quantities: the sum of the distribution \( Q(x) \) and the distribution \( q(x) \) density.

According to \( dQ_r(x) = q_r(X) \, dx \), \( q_r(x) \) is a component of \( dQ_r(X) \), which is contained in the interval \( dx \) for particles from \( x \) and \( x + dx \). The result is a random variable \( r \) (when \( r = 3 \), it means volume distribution; assuming a constant density of tested material, it is also mass distribution), where:

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

This distribution determined the mass share of the particles in the assumed size ranges (CLi) of dust collected in the bottom collector (CS125) by MaScontrol software. The most critical particle size ranges from the point of view of human respiratory tract penetration (< 2.5 µm, 2.5–4 µm, 4–10 µm) were used to calculate the mass share of fine particles in the total mass of dust.

### Calculation of the finest particles content

The calculation of the mass share of particles < 2.5 µm, 2.5–4 µm, 4–10 µm in the whole mass of dust created was performed as follows:

\[
c_i = c_{S125 \cdot CLi}
\]
The results of the sieve analysis are shown in Table 2. The sanding dust generated in this study has fine particle sizes. The fraction of the dust with the greatest mass share is always the fraction collected in the bottom of the set of sieves below the sieve 125 µm. There are some differences in the value of this share. For each wood species, the lowest percentage was measured in the case of dust created during modified sanding of the wood at 220°C. It suggests that the modification temperature can influence the sanding process. Dust particles of larger sizes are generated during the modified sanding of the wood at the highest temperature. But the sieve analysis can provide only a general particle size distribution; the particle content must be determined using a complementary method.

<table>
<thead>
<tr>
<th>Sieve aperture size (µm)</th>
<th>Percentage share of dust fractions</th>
<th>Spruce</th>
<th>Oak</th>
<th>Meranti</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spruce</td>
<td>Oak</td>
<td>Meranti</td>
<td></td>
</tr>
<tr>
<td></td>
<td>untreated</td>
<td>modified at 160°C</td>
<td>modified at 220°C</td>
<td>untreated</td>
</tr>
<tr>
<td>Bottom</td>
<td>86.11</td>
<td>92.63</td>
<td>61.68</td>
<td>94.72</td>
</tr>
<tr>
<td>125</td>
<td>13.25</td>
<td>7.14</td>
<td>34.3</td>
<td>4.48</td>
</tr>
<tr>
<td>250</td>
<td>0.35</td>
<td>0.1</td>
<td>3.87</td>
<td>0.6</td>
</tr>
<tr>
<td>500</td>
<td>0.15</td>
<td>0.1</td>
<td>0.15</td>
<td>0.2</td>
</tr>
<tr>
<td>1000</td>
<td>0.15</td>
<td>0.05</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2000</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The results of the particle size distribution by a laser diffraction method are shown in Fig. 3. The distributions depicted on the graphs were used to determine the dust particle share in the assumed size ranges (C_Li) of dust collected in the bottom collector (C_S125).

Based on the above results, the mass share of particles < 2.5 µm, 2.5–4 µm, 4–10 µm in the whole mass of dust created was calculated. The statistical analysis results and direct comparison of these mass shares are shown in Table 3 and Fig. 4.
Table 3

Analysis of variance (ANOVA) tables for the finest particle mass share of untreated and thermally modified spruce, oak, and meranti wood dust, taking into account the effect of heat treatment and particle size

<table>
<thead>
<tr>
<th>Effect</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce Intercept</td>
<td>80.20411</td>
<td>1</td>
<td>80.20411</td>
<td>92.74634</td>
<td>0.000000</td>
</tr>
<tr>
<td>Heat treatment (factor a)</td>
<td>16.12952</td>
<td>2</td>
<td>8.06476</td>
<td>9.32592</td>
<td>0.000260</td>
</tr>
<tr>
<td>Particle size (factor b)</td>
<td>20.80817</td>
<td>2</td>
<td>10.40408</td>
<td>12.03106</td>
<td>0.000033</td>
</tr>
<tr>
<td>a × b</td>
<td>6.66957</td>
<td>4</td>
<td>1.66739</td>
<td>1.92814</td>
<td>0.115497</td>
</tr>
<tr>
<td>Error</td>
<td>59.66902</td>
<td>69</td>
<td>0.86477</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oak Intercept</td>
<td>1208.43</td>
<td>1</td>
<td>1208.43</td>
<td>668.787</td>
<td>0.000000</td>
</tr>
<tr>
<td>Heat treatment (factor a)</td>
<td>236.822</td>
<td>2</td>
<td>118.411</td>
<td>65.5327</td>
<td>0.000000</td>
</tr>
<tr>
<td>Particle size (factor b)</td>
<td>627.237</td>
<td>2</td>
<td>313.618</td>
<td>173.5674</td>
<td>0.000000</td>
</tr>
<tr>
<td>a × b</td>
<td>128.393</td>
<td>4</td>
<td>32.098</td>
<td>17.7642</td>
<td>0.000000</td>
</tr>
<tr>
<td>Error</td>
<td>124.676</td>
<td>69</td>
<td>1.807</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meranti Intercept</td>
<td>478.7123</td>
<td>1</td>
<td>478.7123</td>
<td>642.0294</td>
<td>0.000000</td>
</tr>
<tr>
<td>Heat treatment (factor a)</td>
<td>137.7533</td>
<td>2</td>
<td>68.8766</td>
<td>92.3745</td>
<td>0.000000</td>
</tr>
<tr>
<td>Particle size (factor b)</td>
<td>287.0063</td>
<td>2</td>
<td>143.5032</td>
<td>192.4606</td>
<td>0.000000</td>
</tr>
<tr>
<td>a × b</td>
<td>68.85080</td>
<td>4</td>
<td>17.2127</td>
<td>23.085</td>
<td>0.000000</td>
</tr>
<tr>
<td>Error</td>
<td>49.2112</td>
<td>66</td>
<td>0.7456</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SS – the sum of squares, df – degrees of freedom, MS – mean squares, F – Fisher's F-test

The analysis of variance confirms the significant importance of the influence of the prior thermal modification (factor a) on the dimensional characteristics of the dust generated during wood sanding and the share of the finest particles fractions of the dust (factor b), which, when dispersed in the air, may constitute thoracic and respirable dust. Furthermore, the interaction between factors (a) and (b) was confirmed in the case of oak and meranti wood dust. In the case of spruce wood dust, there is no such interaction (marked gray row in Table 3).

Among the cases examined, oak wood dust is characterized by the highest average share of the finest particles (of all assumed ranges, i.e., <2.5 µm, 2.5–4 µm, 4–10 µm). This statement applies to both untreated and thermally modified wood dust. Overall, these results suggest that sanding dust from thermally modified wood is characterized by a lower average share of potentially harmful particles which, when dispersed in the air, may constitute thoracic and respirable dust (for all levels of discrimination – size ranges) than for sanding dust from untreated wood. This regularity is not confirmed only by the results of the analysis of dust samples from spruce wood.
Table 3
Statistical analysis of fine particle mass share of untreated and thermally modified spruce, oak, and meranti wood dust

<table>
<thead>
<tr>
<th>Treatment option</th>
<th>Particle mass share (%)</th>
<th>&lt; 2.5 µm</th>
<th>&lt; 4 µm</th>
<th>&lt; 10 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce</td>
<td>Untreated</td>
<td>0.49&lt;sub&gt;ab&lt;/sub&gt; ±0.39</td>
<td>0.62&lt;sub&gt;ab&lt;/sub&gt; ±0.49</td>
<td>1.40&lt;sub&gt;ab&lt;/sub&gt; ±1.55</td>
</tr>
<tr>
<td></td>
<td>Thermally modified at 160°C</td>
<td>0.86&lt;sub&gt;b&lt;/sub&gt; ±0.48</td>
<td>1.13&lt;sub&gt;b&lt;/sub&gt; ±0.64</td>
<td>2.93&lt;sub&gt;b&lt;/sub&gt; ±1.99</td>
</tr>
<tr>
<td></td>
<td>Thermally modified at 220°C</td>
<td>0.36&lt;sub&gt;a&lt;/sub&gt; ±0.22</td>
<td>0.46&lt;sub&gt;a&lt;/sub&gt; ±0.35</td>
<td>0.90&lt;sub&gt;a&lt;/sub&gt; ±0.76</td>
</tr>
<tr>
<td>Oak</td>
<td>Untreated</td>
<td>2.72&lt;sub&gt;b&lt;/sub&gt; ±0.39</td>
<td>3.67&lt;sub&gt;b&lt;/sub&gt; ±0.43</td>
<td>12.90&lt;sub&gt;b&lt;/sub&gt; ±1.64</td>
</tr>
<tr>
<td></td>
<td>Thermally modified at 160°C</td>
<td>1.28&lt;sub&gt;a&lt;/sub&gt; ±0.41</td>
<td>1.43&lt;sub&gt;a&lt;/sub&gt; ±0.58</td>
<td>4.47&lt;sub&gt;a&lt;/sub&gt; ±2.14</td>
</tr>
<tr>
<td></td>
<td>Thermally modified at 220°C</td>
<td>0.98&lt;sub&gt;a&lt;/sub&gt; ±0.42</td>
<td>1.63&lt;sub&gt;a&lt;/sub&gt; ±0.65</td>
<td>6.46&lt;sub&gt;a&lt;/sub&gt; ±2.69</td>
</tr>
<tr>
<td>Meranti</td>
<td>Untreated</td>
<td>2.00&lt;sub&gt;b&lt;/sub&gt; ±0.40</td>
<td>2.24&lt;sub&gt;b&lt;/sub&gt; ±0.43</td>
<td>9.01&lt;sub&gt;b&lt;/sub&gt; ±1.94</td>
</tr>
<tr>
<td></td>
<td>Thermally modified at 160°C</td>
<td>0.82&lt;sub&gt;a&lt;/sub&gt; ±0.09</td>
<td>0.85&lt;sub&gt;a&lt;/sub&gt; ±0.24</td>
<td>3.21&lt;sub&gt;a&lt;/sub&gt; ±0.72</td>
</tr>
<tr>
<td></td>
<td>Thermally modified at 220°C</td>
<td>0.49&lt;sub&gt;a&lt;/sub&gt; ±0.06</td>
<td>0.58&lt;sub&gt;a&lt;/sub&gt; ±0.12</td>
<td>3.62&lt;sub&gt;a&lt;/sub&gt; ±1.29</td>
</tr>
</tbody>
</table>

Mean value (n = 9) ± standard deviation; identical superscripts (a, b, c) indicate a non-significant difference (p < 0.05) between mean values according to post hoc Tukey's test.

The statistical analysis results show that the average mass share of the finest dust fractions isolated from the dust generated during the sanding of oak and meranti wood does not depend on the parameters of the previous thermal modification process. In the cases discussed, the average mass shares of these dust fractions (for all levels of discrimination – size ranges) generated during the sanding of modified wood at 160 and 220 °C do not differ significantly (p < 0.05).

4 Discussion

The results align with the earlier studies on dust from modified wood performed by different authors. There is a general opinion that the thermal modification of wood does not influence the sizes of dust particles generated during sanding-modified wood. Other factors, such as species, wood density, and processing parameters, are more crucial in wood dust generation. However, some studies report an increase in the generation of fine wood dust during the mechanical processing of thermally modified wood. The most important examples of earlier results are described below.

Kučerka and Očkajová (2018) studied the dust of Sessile oak (Quercus petraea) and Norway spruce (Picea abies). The wood, after the thermal modification in four variants of temperatures, 160, 180, 200, and 220°C, by 3h, was sanded on a vertical narrow-belt sander with P80 paper. The set of sieves with aperture sizes 2000, 1000, 500, 250, 125, 80, 63, and 32 µm was used in the sieve analysis. The fine particle size fraction (≤ 80 µm) of oak dust showed the highest mass share for all treatment temperatures; simultaneously, the lowest values of the dust fraction with a size of ≤ 80 µm were obtained at the processing temperature of 220°C for both wood species studied. The authors pointed out that the increase in treatment temperature does not significantly affect the amount of dust generated.
The authors explained the high amount of the finest particles created during sanding by the decreased wood density resulting from increased temperature during the modification process.

Očkajová et al. (2019) studied the relationship between the density of untreated wood, wood after thermal modifications at four temperatures (160, 180, 200, and 220°C), and the properties of dust created by sanding with a belt sander using P80 sanding paper. Three species of wood were tested: Sessile oak (*Quercus petraea*), Norway spruce (*Picea abies*), and Meranti (*Shorea acuminata*). A set of sieves, 2000, 1000, 500, 250, 125, 80, 63, and 32 µm, was used to assess the dust particle size distribution. The fraction of fine particles (≤ 80 µm) in thermally modified oak dust was similar to that of untreated wood's fine dust. The mass of this fraction was 92–95%. A significant decrease in the mass share of this fraction was observed in the dust from wood modified at 220°C. The highest mass share of dust with a particle size of ≤ 80 µm for other wood species was measured in dust from modified wood at a temperature of 160°C (87% - meranti, 93% - spruce). This share decreased with increasing temperature of wood modification. A similar influence of temperature was observed in the smallest sieve fraction (32 µm) and on the bottom of the sieve (a fraction with the finest particle sizes < 32 µm). The authors explained the sieve analysis results with the reduced density of thermally modified wood.

Processing technology influences the particle size distribution of wood dust. Očkajová et al. (2020b) studied the granulometric composition of chips and dust from the longitudinal milling and sanding of thermally modified oak and spruce wood at four modification temperatures: 160, 180, 200, and 220°C. Sieve analysis included 2000, 1000, 500, 250, 125, 80, 63, and 32 µm sieves. The results showed that the residual curves show the difference in particle size distribution in the two technologies. The sanding dust residue curves shift to the right due to the increased temperature of the wood treatment (higher mass share of large particles), while the milling dust residue curves shift to the left due to the increased temperature of the wood treatment (higher mass of small particles). This observation is also confirmed by earlier literature reports on oak sanding dust (Marková et al. 2016; Očkajová et al. 2018b).

Očkajová et al. (2020a) studied the particle size distribution in dust generated during longitudinal milling of thermally modified spruce and oak. The variables in the experiment were the modification temperature (160, 180, 200, and 220°C), and the feed rate (6, 10, and 15 m·min⁻¹). The particle size distribution measurements were made with a set of sieves (2000, 1000, 500, 250, 125, 80, 63, and 32 µm). The authors observed that the mass share of the coarse, fine, and very fine dust fractions changes with increasing wood modification temperature. The results of the study showed that the amount of sieve fraction with particles ≤ 80 µm increased in oak and spruce only after applying the highest temperatures, i.e. 200 and 220°C.

Kminiak and Dzurenda (2019) investigated the changes in the particle size distribution of wood chips due to thermal wood treatment. They used maple (*Acer pseudoplatanus*) wood particles formed during milling in a 5-axis CNC machining center for analysis. The analysis showed that more than 2/3 of the dust particles produced were coarse-grained fractions > 100 µm. The mass share of particles with a size smaller than 125 µm, did not exceed 2.5%. The thermally modified maple wood did not form the finest dust particles. The results did not confirm the thesis suggested by earlier authors that changes causing an increased share of fine dust fraction occur as a result of the heat treatment on the wood's chemical structure.

The above-cited research results suggest that the thermal modification reduces the dust fraction with a particle size ≤ 80 µm. An example is the cited study of dust waste from sawing oak and pinewood (Dzurenda et al. 2010), milling and sanding oak, and spruce wood (Očkajová et al. 2020b, a). Furthermore, in scientific publications on the dust generated during thermally modified wood (oak, spruce, meranti), based on the sieve analysis performed, a lower particle content of particles with the smallest size was found in the modified dust from the wood at the highest
temperature (220 °C) (Kučerka and Očkajová 2018; Očkajová et al. 2019). The absence of the finest particles, i.e. < 32 µm, was also found. Kminiak and Dzurenda (2019) proposed a similar conclusion based on their research on dust from milling maple wood. The authors also stated that there were no significant differences in particle sizes for modified and untreated wood dust.

Additionally Mikušová et al. (2019) investigated the influence of various thermal treatment temperatures on the size distribution of wood dust created by a hand-held belt sander. Test samples were made of meranti (Shorea acuminata) wood. The untreated and thermally modified samples at temperatures of 160, 180, 200, and 220°C samples were compared using the optical and gravimetric methods. The mass share of the finest particles in tested wood dust was highest at the treatment temperature of 160°C. However, the authors stated that mass proportion mass was not significantly influenced by thermal treatment.

The occurrence of the finest particles (≤ 10 µm) in the dust created by untreated and thermally modified wood of five species (aspen, fir, maple, ash, and poplar), was also investigated. Thermal modification of wood did not affect the amount of these particles in the air (Aro et al. 2019). (Majka et al. 2022) compared the dust from untreated beechwood to the dust from thermally modified beechwood (200°C, 3 h). The dust were separated into four sieve fractions with grain sizes < 25 µm, 25–80 µm, 80–250 µm, and > 250 µm. The authors studied whether the thermal modification changes the particle size distributions and whether all four dust sieve fractions contain the finest particles. The wood materials were sanded with P120 paper. Both types of tested dust had similar particle size distributions. Based on measurements using a laser particle sizer, the presence of particles < 10 µm in each of the four fractions was found.

Such statements contradict the research results described by other authors. An example of such research is the work of (Hlásková et al. 2018). On the basis of the sieve analysis results, these authors found that the increased modification temperature of beech wood resulted in a reduced mass share of the smallest particles in the dust created in sanding. However, in the dust of wood modified at higher temperatures, the microscopic image analysis showed a higher content of the finest particles. The use of the laser diffraction analysis method to assess the mass share of the finest particles in the undersieve fraction (containing the smallest particles) also allowed the conclusion that when milling modified pine wood, the modification temperature influences the higher mass share of the finest particles in the resulting dust (Piernik et al. 2019).

Therefore, there is still uncertainty as to whether and to what extent, depending on the type of wood and the method of processing, thermal modification affects the increase in the mass share of fine dust. This is a reason for further research in this area so that the knowledge base is large enough to clearly assess this impact.

5 Conclusions

The experimental setup included three types of wood (European softwood, European hardwood, Asian hardwood), and two extreme temperatures of modification (low and high). Test samples were processed with the most dust-generated technology (sanding). The sieve and laser analysis methods were used in the dust fraction analysis. Among the examined cases, oak wood dust is characterized by the highest average mass share of the finest particles (of all assumed ranges, i.e. <2.5, 2.5-4 and 4~10 µm), which, when dispersed in the air, may pose a health risk to workers in the surroundings of workstations. This statement concerns the dust of untreated and thermally modified wood.
Generally, sanding dust from thermally modified wood generates a lower average mass share of potentially harmful particle fractions than sanding dust from untreated wood. It was observed for all levels of discrimination. This regularity is not confirmed only by analyzing the results of the spruce dust sample. This may be a result of the generally low average mass share of these fractions and the relatively large dispersion of the results, which may be the effect of the irregularity of the spruce dust particle shape. The irregularity in the shapes worsens the accuracy of the measurement methods used to determine the size of the wood dust particles.

Extreme temperatures were used in the thermal modification of wood, a low (160°C) and a highest (220 °C); it should be assumed that the above two statements about the generally lower mass share of potentially harmful particle fractions compared to the dust generated when sanding untreated wood, as well as there are no statistically significant differences in the average mass share of the finest fractions, are valid at all intermediate temperature variants used in thermomodification of woods.

Declarations

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Figures

Figure 1

Heat treatment: a – chamber, b – schedule
Figure 2

Narrow belt sander JET JSG-96
Figure 3

Averaged cumulative distribution ($Q_3$) and density distribution ($q_3$) of untreated and thermally modified wood dust: (a) spruce, (b) oak, (c) meranti. ($n = 9$ for each variant)

Figure 4

Comparison of the average values of the finest fractions of untreated and thermally modified wood dust: (a) spruce, (b) oak, (c) meranti, error bars depicted ± 95% confidence limits.