# Characteristics of Thermally Modified Hardwood Dust in Determining Workers' Occupational Exposure

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Thermal modification of wood changes its mechanical properties, generally reducing its strength, such that it is more easily chipped during processing than untreated hardwood. This study presents specific parameters used in the determination of mass concentration of thermally modified (TM) hardwood by gravimetric and photometric methods. An optical device, the Split 2, was used in the active mode, of which the holder of the inhalable dust IOM (Institute of Occupational Medicine) filter was the input part. Side-by-side determination of the respirable and inhalable mass concentration was made using the Higgins-Dewell respirable dust cyclone and an inhalable dust IOM sampler. Side-by-side determination of inhalable and total dust mass concentration was made using an IOM and open-faced (OF) filter holder to establish an IOM / OF sampling ratio. A correction factor of 1.16 was calculated for applying the photometric method as the ratio of mass concentration determined by gravimetric and photometric methods. Minimal concentrations of respirable and inhalable wood dust (geometric mean: $c_r$ = 0.058 mg/m$^3$; $c_{inh}$ = 0.882 mg/m$^3$) and a 12.76% share of respirable dust in the inhalable concentration $c_r$ / $c_{inh}$, had a significant influence on the efficiency of the photometric method. The mass concentration obtained by IOM and OF samplers did not significantly differ (p = 0.36).

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*Keywords: Wood dust mass concentration; Gravimetric method; Photometric method; Correction factor; IOM / OF conversion factor; Respirable dust*

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## INTRODUCTION

Wood dusts, especially from hardwood species, are classified as carcinogenic substances according to the European Directive 2017/2398 on the protection of workers from the risks related to exposure to carcinogens or mutagens. Increased risk of worker exposure to inhalable wood dust refers to 16% and 25% of the number of workers exposed to mass concentrations of up to 5 mg/m$^3$ and up to 2 mg/m$^3$, respectively (Kauppinen *et al*. 2006). European Directive 2017/2398 prescribes a limit value of 2 mg/m$^3$ (3 mg/m$^3$ until 17$^{th}$ January 2023), which refers to the mass concentration measured or calculated in relation to a reference period of an 8-h exposure of workers.

Wood does not have to be treated with environmentally unacceptable protective agents if chemical changes, due to thermal modification in wood, achieve a reduction in hygroscopicity, improved biological resistance, and dimensional stability. Thermally modified wood has advantages in properties, such as reduced moisture absorption, dimensional stability, biological resistance, the attractive appearance of TM (thermally modified) wood, the possibility of using wood without surface treatment, a long-life cycle, lower thermal conductivity, higher surface hardness, greater crack resistance, *etc.* (Očkajová *et al*. 2020). However, thermal modification also leads to the degradation of hemicellulose, cellulose, and lignin, *i.e.*, mechanical changes that reduce the initial strength of the wood, which causes it to crumble more during processing and to produce more dust in the workspace (Beljo Lučić *et al*. 2009; Pervan 2009; Krauss *et al*. 2016). The thermal modification of wood with a temperature higher than 150 °C causes a change in the composition of the cell wall, and consequently a change in the physical and mechanical properties of the wood – reduced tensile and bending strength, decreased weight and density, increased hardness, and compressive strength parallel to the fibres, increased modulus of elasticity, increased brittleness, and reduced impact strength (Piernik *et al*. 2018; Očkajová *et al.* 2019). Degradation of the cell wall of hemicelluloses causes the development of nano- and micro-cracks, where the consequent reduction of wood strength and toughness limit the use of TM wood, in construction (Očkajová *et al*. 2020). Ratnasingam and Ionas (2012) found that dust emission during sanding of heat-treated rubberwood produced significantly higher proportions of finer dust compared to the machining of conventionally kiln-dried samples.

Additionally, reducing the density of wood by increasing the temperature of the modification process has an important impact on the distribution of particles within the fine dust produced from sanding, because in this case, the particles are formed by easier separation and are larger in size than in wood with a higher density (Očkajová *et al*. 2019). The application of the photometric method of determining the mass concentration of floating particles should be preceded by a knowledge of the specific properties of aerosols. In general, the photometric method is recommended to be applied using a previously obtained correction factor for specific operating conditions. The properties of the floating particles of wood chips under production conditions can vary in an extremely large number of ways. The reliability and precision of the optical detector for determining the mass concentration of aerosols depends on many influencing factors: the type, structure, density and shape of the particle, refractive index of the particle, aerodynamic diameter of the particle, relative humidity of the surrounding air, water content of the wood, and the concentration of particles and distribution of fractions in the aerosol (Thomas and Gerbhart 1994; Lanki *et al*. 2002; O'Shaughnessy and Slagley 2002; Tatum *et al.* 2002; Dado *et al*. 2017). The efficiency of the photometric method was found to decrease with increasing aerodynamic particle diameter (Koch *et al*. 1999; Koch *et al*. 2002; Tatum *et al*. 2002; Rando *et al*. 2005a,b). The shape of the floating wood particle is fibrous, that is, the ratio of the length to the width of the particle is greater than 3 (Beljo Lučić *et al*. 2005). Consequently, the complexity of using photometry to determine the mass concentration of wood dust is reflected in the wide range of the correction factor of the device from 1 to 4.5 (Čavlović *et al*. 2009). However, for particles with an aerodynamic diameter of less than 10 µm, the obtained photometry efficiency was equal to the efficiency of the reference IOM collector (correction factor approximately 1) (NIOSH 1998; Rando *et al*. 2005a). The correction factor for any type of aerosol is determined from the ratio of mass concentrations measured by the gravimetric method to the mass concentrations measured by infrared radiation during photometer measurements (NIOSH 1998). The photometric method usually underestimates the results of mass concentration obtained by the gravimetric method. To obtain an accurate measure of airborne particle concentration, the aerosol monitor should always be compared to a reference gravimetric dust sampler to determine an average calibration factor (Thorpe and Walsh 2007, 2013; Halterman *et al*. 2018). In the processing of thermally modified and unmodified wood, different particle size distributions of chipped wood are possible and, consequently, the distribution of fractions of floating particles in the surrounding air of the room. Dzurenda and Orłowski (2011) studied particle size distribution of ash wood sawdust and Dzurenda *et al*. (2010) analysed oak wood sawdust at different feed speeds and concluded that TM sawdust is finer than unmodified sawdust. For longitudinal milling, the percentage of fine and very fine fractions increased as wood modification temperatures increased, especially when compared to the coarse fraction of native wood (Očkajová *et al*. 2020).

The share of respirable mass concentration in inhalable dust mass concentration ($c_r$ / $c_{inh}$) or in total dust ($c_r$ / $c_{tot}$) depends on numerous factors of particle formation and, as a rule, the share $c_r$ / $c_{inh}$ and $c_r$ / $c_{tot}$ increases with decreasing dustiness (Sass-Kortsak *et al*. 1986; Muranko *et al*. 2001; Kos *et al*. 2004; Noto *et al*. 2016; Čavlović *et al*. 2022). In accordance with the attempt to harmonize the results of mass dust concentration measurements obtained with different filter holders, the conversion factors of total dust concentration to inhalable fraction concentration were determined depending on the sampler used. Many authors have compared the results of comparative personal or static sampling, calculating the conversion factor for a pair of filter holders using the Institute of Occupational Medicine (IOM) inhalable dust sampler, Gesamtstaub-Probenahmesiystem (GSP), open- and close-faced filter cassette (metal and plastic), 7-hole sampler (7HS), CIP10-I CIP10-I, or 37 mm open and close-faced filter cassette (plastic) (Vaughan *et al*. 1990; Kenny *et al*. 1997; Davies *et al*. 1999; Harper and Muller 2002). Croatia has replaced the 25-mm open-faced sampling head (OF) with the IOM sampler to accommodate the EU requirements. Previous research has shown that mass concentration obtained by IOM and OF samplers did not significantly differ. The obtained IOM / OF ratios (conversion factor) ranged between 0.7 and 2.3 and could be valid for an environment with a higher dust mass concentration, between 1 and 7 mg/m$^3$ (Čavlović *et al*. 2013). Szewczyńska and Pośniak (2017) applied a conversion factor of 1.59 to calculate the total to inhalable fraction concentration, for 37-mm closed-faced cassette and IOM sampler in the ambient air of a furniture factory with very high inhalable (1.34 to 22.13 mg/m$^3$) and respirable (0.38 to 4.04 mg/m$^3$) mass concentrations. Harper and Muller (2002) compared the IOM sampler with the 'total' dust close-faced cassette (CFC) and found that the larger ratios IOM / CFC, which varied between 1.2 and 19 with a median of 3.4, were associated with higher dust concentrations in the wood industry. Noto *et al*. (2016) found results of the median ratios IOM / CFC between the observed exposures of inhalable and 'total' dust was an average of 2.2. The aim of that study was to present specific parameters (correction factor for optical device, the share of respirable in inhalable dust and the conversion factor IOM / OF) in the determination of mass concentration of TM hardwood dust, by gravimetric and photometric methods. The analysis aims to show the influence of specific properties of TM wood on the efficiency of the optical method related to the share of respirable dust in inhalable dust.

## EXPERIMENTAL

### Materials

Sampling was completed in a production plant that produces wooden floors during the processing of ash wood with a circular saw, a four-sided planer, and a machine for making edge profiles. Thermally modified ash wood (*Fraxinus angustifolia*) was obtained by drying at 90 °C to 126 °C and heat treatment at 126 °C to 205 °C, together lasting for 20 hours, and then gradual cooling for 3 h. The sample pairs of inhalable ($N_I$ = 15) and total wood dust ($N_T$ = 14), then respirable ($N_R$ = 10) and inhalable ($N_I$ = 10) samples were collected side-by-side for 8 h using the gravimetric method. Using the photometric method, the inhalable wood dust samples were collected ($N_{PH}$ = 10 and $N_G$ = 10) for 2 h.

## Methods

*Gravimetric determination of wood dust mass concentration*

Determination of the mass concentrations of respirable, inhalable, and total wood dust from ambient air was performed using personal sampling pumps and three types of filter holders: Higgins-Dewell respirable dust cyclone manufactured by Casella (Bedford, UK), inhalable dust IOM sampler manufactured by SKC Ltd. (Dorset, UK), and total dust 25-mm open-faced filter holder by Casella. Recommendations for wood dust sampling include the convention for measuring airborne particles as specified in EN 481 (1993) and CEN/TR 1520 (2005). When a mixture of particles of varying sizes is inhaled, larger particles settle in the upper part of the respiratory tract (inhalable fraction) and smaller particles penetrate deeper into the respiratory system, through the tracheobronchial zone to the alveoli (respirable fraction). The inhalable fraction is the mass fraction of total floating particles inhaled through the nose and mouth. The respirable or alveolar fraction is the mass fraction of inhaled particles that penetrate the alveoli.

Ten Casella Apex personal sampling pumps were used per day, set at a suction flow rate of 2 L/min to determine the mass concentration using an inhalable dust IOM sampler and a total dust open-faced sampler, or set at 2.2 L/min using a respirable dust cyclone sampler. The measuring equipment, including a personal sampling pump and filter holder, are fixed, stationary, in accordance with the requirements of the optical device, which is mounted stationary because of its sensitivity. CEN/TR 15230 (2005) states that it is possible to use personal samplers for stationary collection.

Whatman 25-mm quartz filters (QM-A) were conditioned in the desiccator at 20 ± 1 °C and 47.5 ± 2.5% relative humidity for 48 h before weighing, both before and after the sampling. After the first weighing, the conditioning was repeated under the same conditions for a period of 24 h and the filters were weighed again. Filter separation efficiency is at least 99.5% for particles with an aerodynamic diameter of 0.3 μm. Each filter was electrostatically discharged prior to weighing, using a Mettler Toledo U-electrode. The weighing was performed using a micro-scale Mettler-Toledo MX-5 (Mettler-Toledo International Inc., Greifensee, Switzerland) with $10^{-6}$ g scale sensitivity. The mass concentration of dust was determined using the gravimetric method in accordance with the standard ZH 1/120.41 (1989).

*Photometric determination of wood dust mass concentration*

The optical device, the Split 2 model, manufactured by SKC Ltd. (Dorset, UK, 2006), for the continuous measurement of mass concentration of floating particles, consists of a device for data processing with a display, and an input part that consists of an inhalable dust IOM filter holder and the optical part of the device.

The optical part of the device uses an infrared light source located at an angle of 90° to the photodetector. The optical device is connected to a Casella pump (Bedford, UK, 2001), set to an air flow of 2 L/min. The air sample passes through an optical sensor (photometric) and then through a filter holder (gravimetric) (Fig. 1).

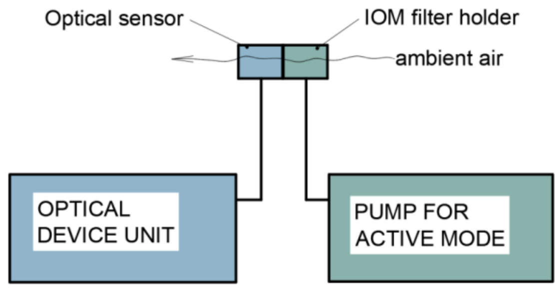


**Fig. 1.** Optical device connected to the pump and optical input part with an IOM filter holder

The instructions of the National Institute for Occupational Safety and Health (NIOSH) Method 0600 (1989) from the *Manual of Analytical Methods* (NMAM), were applied when using the device for continuous determination of mass concentration. Wood dust samples were collected for 2 h in dry wood processing. To achieve the reliability of continuous measurement with this device, the correction factor was determined from the mean value obtained from at least 10 repetitions. The correction factor for continuous determination of mass concentration was obtained as the ratio of mass concentration determined by gravimetric and photometric methods. The stationary method of collecting samples was chosen because of the required precision of the optical part of the device which is sensitive.

*Calculation of the limit of detection (LOD)*

Because the use of a blank was difficult, because of the tiny masses of the samples, the mass limit of detection was obtained from the standard deviation ($s_m$) of the lowest masses ($m_{min}$), from a few samples selected from the group of samples collected from the same woodworking place. The limit of detection was calculated as three times the value of the standard deviation (HRN CEN/TR 15230 2005). All sample masses where higher than the calculated LOD values, except for one sample of respirable fraction that was removed from the calculation.

*Statistical analysis*

The geometric mean, as a better indicator of dust emission than the arithmetic mean, was chosen to show the average value of the mass concentration of wood dust (mass concentrations have a log-normal distribution). Pearson's correlation analysis was made using Excel 2016 (Microsoft Corp., Redmond, WA, USA). Statistical differences in mass concentrations between samples collected by different methods, or using different filter holders, were tested using the Student's t-test. Descriptive statistics of variables and statistical analyses were performed using the statistical software - STATISTICA 14.0.0.15 (Statsoft Inc., Tulsa, OK, USA).

## RESULTS AND DISCUSSION

### Correction Factor for Optical Device

The mean value of all obtained optical device correction factors was 1.16, ranging from 0.45 to 2.75 for continuous optical determination of the mass concentration, and was calculated as the ratio of mass concentration determined by both the gravimetric and photometric methods (Table 1).

**Table 1.** Comparison of Inhalable Mass Concentration Obtained Gravimetrically and Photometrically

| Type of Method | N | Mass Concentration | Homogeneity of Variances Test | | t-Test | Correction Factor ($c_g$ /$c_{ph}$) |
|---|---|---|---|---|---|---|
| | | (mg/m$^3$) | F | p | p | |
| Gravimetric | 10 | 0.80 | 1.928 | p > 0.05 | 0.74 | 1.16 |
| Photometric | 10 | 0.79 | | | | |

In spite of the large data distribution, statistical testing using the Student's t-test showed that these two groups of mass concentration values, obtained by gravimetric or photometric methods, were not significantly different ($p = 0.74$). The results of determining the correction factor for the optical device showed the high efficiency of the photometric method, whereby the photometrically obtained mass concetration does not underestimate the mass concentration obtained by the gravimetric method. These results are in accordance with other findings on the reliability of the photometric method, which have shown the best photometric sensitivity for particles of 0.6 μm at a constant low mass concentration (NIOSH 1998). In addition, when measuring lower mass concentrations, the errors of the gravimetric method, because of the manipulation of the filters, should be taken into consideration (Rando *et al*. 2005a).

Previous research into the correction factor of untreated dry oak and beech wood resulted in higher correction factors of 2 to 3 for the same mechanical processing and the same level of inhalable dust in the work area (Čavlović *et al*. 2021). Additionally, the obtained high efficiency of the optical method can be caused by the specific particle size distribution of very fine dust, and the great number of particles of easily fragmented TM hardwood. Granulometric analysis has shown the greater fragmentation of treated wood (ash, oak, and pine) compared to untreated wood (Dzurenda *et al*. 2010; Dzurenda and Orlowski 2011; Barcík and Gašparík 2014; Krauss *et al*. 2016; Piernik *et al*. 2018). Hlásková *et al.* (2015) found that there are more particles with the characteristic sizes below 4 μm and 10 μm in sawdust from modified wood. 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 to 1.67 m/min$^1$). Dzurenda *et al* (2010) found that the sawdust created at the same feed speed during the sawing of TM 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.* (2011) and Barcík and Gašparík (2014), stated that the tooling of modified wood is a source of finer dust particles. In all cases, most of the dust production occurred in the coarser inhalable fraction with nearly 10 times more dust than in the finer respirable range (Hursthouse *et al*. 2004). The efficiency of the photometric method depends on the water content in the wood, on the wood species, and on the mechanical processing. However, the results imply a significant influence of the particle size distribution that predominates at a relatively low concentration.

The change in the physical and mechanical properties of TM wood has a complex effect on the distribution of particles of chipped TM wood, mainly because of the reduction of wood density, and depending on the modifying temperature. The emission of wood dust into the surrounding air and the formation of aerosols in the workspace are mostly determined by the properties of the fine particles created during the mechanical processing of wood, especially during sanding. Očkajová *et al.* (2019) stated that in the sanding process a higher share of dust particles was not created with increasing the modifying temperature. Granulometric analysis of TM oak wood dust recorded, only at the temperature of 220 °C, a high share of wood dust particles in the 0.250-mm and the 0.125-mm sieves compared to the value in thermally unmodified wood. However, the share of wood dust particles in the 0.032-mm sieve, being the bottom sieve, decreased compared to the value in thermally unmodified wood. The main factor that causes the decrease in the proportion of the spruce and oak dust with dimension ≤ 0.08 mm at 220 °C is the decrease in wood density (Kučerka and Očkajová 2018). In the case of thermally treated meranti wood at temp 220 °C, a decrease in density of TM occurs by 14.11% when compared to untreated wood. The decrease in the average value of the respirable mass concentration of wood treated at 200 and 220 °C was then measured. (Mikušova *et al*. 2019). No significant influence of thermal modification at a temperature of 170 °C on the formation of wood particles of the size $PM_{10}$, $PM_{2.5}$ and $PM_1$ of the five wood species (yellow poplar, red maple, white ash, aspen and balsam fir) when the wood is processed on a typical industrial table saw (Aro *et al.* 2019). The authors Juda *et al*. (2023) could not definitively conclude whether low-thermal treatment affects the amount of dust created, including dust of small fractions, because increased temperatures during heat treatment increase the proportion of fine dust particles smaller than 0.125 mm in size compared to untreated wood, and with heat treatment comes to a decrease in density for birch and alder, but for beech wood there is no significant change in the density of the material.

## The Share of Respirable in Inhalable Mass Concentration

The average value of 12.76% respirable particle share in inhalable dust ranged from 3.81% to 23.34% for a working environment with a low concentration of TM ash wood dust (Table 2). Pearson's correlation test of all measured values obtained with two types of filter holders showed a medium strong correlation (k = 0.7).

**Table 2.** The Share of Respirable in Inhalable Mass Concentration

| Type of Filter Holder | N | Mass Concentration | | | The Share $c_r$ / $c_{inh}$ |
|---|---|---|---|---|---|
| | | Geometric Means | Minimum | Maximum | |
| | | (mg/m³) | | | % |
| Respirable dust cyclone | 10 | 0.058 | 0.013 | 0.145 | **12.76** |
| Inhalable dust IOM sampler | 10 | 0.545 | 0.335 | 0.812 | |

The mass concentration of the respirable fraction increased with increased mass concentration of the inhalable fraction (Fig. 2). The assumption is that, because of the very low concentration of both fractions and the trend shown only up to a concentration of 0.812 mg/m$^3$, the correlation diagram shows an increase in the share $c_r$ / $c_{inh}$ with increasing inhalable mass concentration (Fig. 3).

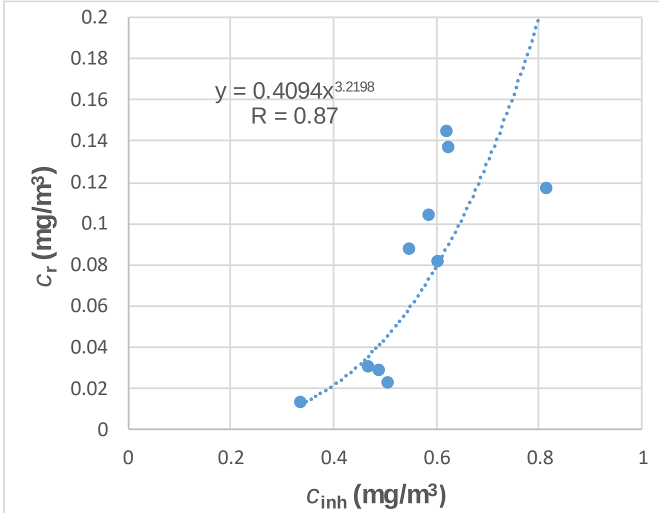


**Fig. 2.** Correlation diagram of respirable and inhalable dust mass concentration

The effectiveness of the optical method regarding the share of respirable inhalable dust could be explained by the results of the 8-h measurement by the gravimetric method. Obviously, the efficiency of the photometric method was influenced by the minimal concentration of the respirable fraction (from 0.013 to 0.145 mg/ $m^3$) within the low concentration of inhalable wood dust. A smaller increase than expected in the proportion of $c_r$ / $c_{inh}$ was also obtained, considering the general phenomenon of greater chipping of TM wood compared to thermally unmodified wood.

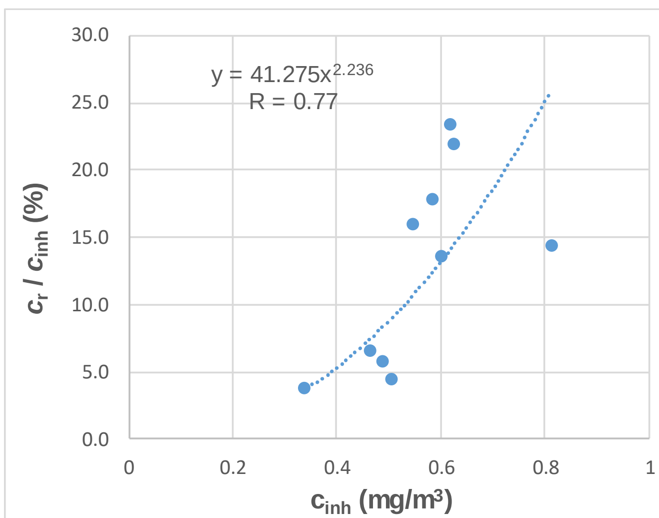


**Fig. 3.** Correlation between the share of respirable in inhalable ($c_r$ / $c_{inh}$) wood dust mass concentration and absolute value of inhalable mass concentration

Generally, the geometric mean values of all inhalable dust mass concentrations (N = 25) obtained by the gravimetric method, amounts to 0.882 mg/$m^3$ (ranging between 0.335 and 2.154 mg/$m^3$), which represents a relatively minimal exposure of workers to wood dust. During the processing of TM ash wood at four side planers and a circular saw in a wooden floor production plant, the mass concentrations of the inhalable dust for one sample of a total of 25 inhalable samples exceeded the value of 2 mg /m$^3$, which is the prescribed exposure limit of increased risk.

In previous research, the highest share of respirable particles in total wood dust, over 50%, was recorded for samples with a concentration of total dust lower than 1 mg/m$^3$ and with cutting parameters that achieved the lowest chip thickness during sanding of oak wood. That research has shown that the share of mass concentration of the respirable fraction in the mass concentration of total dust ($c_r$ / $c_{tot}$) decreases with an increase in the mass concentration of total dust. In such conditions of high concentrations of the respirable fraction (max. 1.8 mg/m$^3$ and average 0.61 mg/m$^3$) and of total dust (max. 8 mg/m$^3$), the trend of change in the $c_r$ / $c_{tot}$ ratio was also influenced by a larger range of inhalable mass concentration values (Kos *et al*. 2004). In determining the occupational exposure of oak wood dust in a furniture factory, the share of $c_r$ / $c_{inh}$ ranged between 12% and 31%, which is approximately 19% of the inhalation fraction on average. In this case, lower values of respirable oak wood mass concentration were measured from 0.69 to 0.462 mg/m$^3$. Additionally, the share of $c_r$ / $c_{inh}$ for samples with inhalable mass concentration exceeding 2 mg/m$^3$ was lower than 16%, with a slightly decreasing tendency (Čavlović *et al*. 2022). In other furniture production industries, the respirable fraction concentrations were 0.38 to 4.04 mg/m$^3$, which represents approximately 25% of the inhalable fraction on average (Szewczyńska and Pośniak 2017). Sass-Kortsak *et al*. (1986) found that the sanding operations produce a higher proportion of respirable dust (22%) than other woodworking operations (6% to 14%). The $c_r$ / $c_{inh}$ ratio was expected to differ between quartiles of inhalation (or total) mass concentration. Similar research was conducted in other industries, for example in the cement industry the mean $c_r$ / $c_{inh}$ ratio was 9% (Noto *et al*. 2016), and in the black carbon industry (Muranko *et al*. 2001) the mean share of respirable in "total" dust concentrations was 37%, both decreasing by increasing the dust mass concentration.

*IOM / OF conversion factor*

The geometric mean of mass concentration for the inhalable fraction 1.22 mg/m$^3$ and for total dust 1.13 mg/m$^3$ are presented in Table 1. Total dust mass concentrations amount between 0.611 and 1.551 mg/m$^3$ and inhalable fraction concentrations were between 0.632 and 2.154 mg/m$^3$. The conversion factor of total dust concentration to inhalable fraction concentration ranged from 0.91 to 1.59. The mean value of IOM / OF conversion factors was 1.12. There was statistically no difference between the mass dust concentration measurements obtained with IOM and those obtained with 25 mm open-faced (OF) filter holders (p = 0.36).

**Table 3.** Comparison of Mass Concentration of TM Inhalable Dust Obtained with IOM and OF Samplers

| Type of Filter Holder | N | *c* [a] | *c* [b] | Homogeneity of Variances Test | | t-Test | Conversion Factor (IOM / OF)[b] |
|---|---|---|---|---|---|---|---|
| | | mg/m$^3$ | | F | p | p | |
| IOM | 15 | 1.22 | 1.27 ± 0.40 | 2.535 | p > 0.05 | 0.36 | 1.12 ± 0.2 |
| OF | 14 | 1.13 | 1.16 ± 0.25 | | | | |

[a]: Geometric means; and [b]: arithmetic means and standard deviations

Pearson's correlation test of all measured values obtained by these two filter holders has shown a strong correlation (k = 0.82). Predicala and Maghirang (2003) also found no significant difference between paired IOM and OF filter holders. Figure 4 presents the distributions of mean mass concentrations and data dissipation measured with the IOM and with a 25 mm OF sampler.

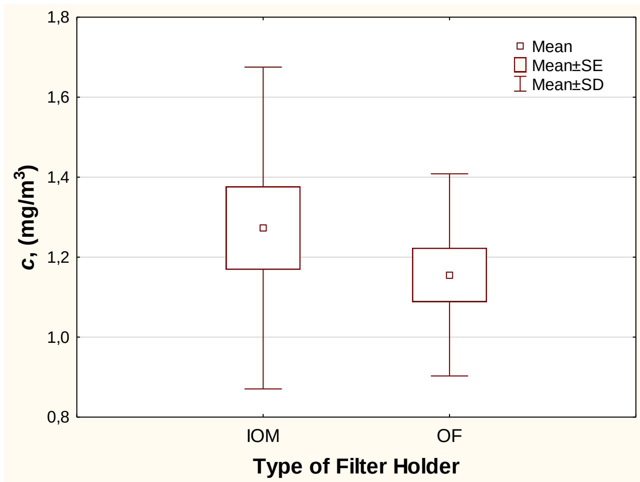


**Fig. 4.** Distribution diagram showing mean values and data dissipation of mass concentration obtained by IOM and OF (SD-standard deviation, SE- standard error of mean)

Greater data dispersion was observed with IOM than with OF measurements, perhaps due to a higher sensitivity of the IOM sampler to different particle size distributions, projectiles, wind speed, shape of inlet, wall deposits, and thus different ways of mounting the sampler may therefore have influenced the observed ratios. Aerosol particles can be electrically charged and therefore stick to the walls of the filter holder and thus contribute to variations in ratios because of differences in weighing procedures (Notø *et al.* 2016).

Szewczyńska and Pośniak (2017) applied the IOM / OF conversion factor of 1.59. Lidén *et al*. (2000) concluded that IOM mass concentration corresponded to approximately double the OF mass concentration. Tatum *et al.* (2001) presented results showing that the relative efficiency of inhalation samplers compared to a total dust sampler can vary as a function of the particle size distribution in the workplace.

In relation to the general increase in dust emissions from TM wood processing and, with the aim of protecting the health of workers from the risks related to wood dust, in accordance with previous results of research, when milling TM wood, it is strongly recommended to use the highest possible cutting depth (Piernik *et al.* 2018) and higher values of feed rate (Očkajová *et al*. 2020).

## CONCLUSIONS

1. The results indicate a significant influence of the particle size distribution of aerosols, which prevails at relatively low concentrations, in determining the efficiency of the photometric method and obtaining a correction factor for its application in determining the mass concentration of inhalation dust of TM hardwood. The efficiency of the

photometric method was influenced by the minimum concentration of the respirable fraction (from 0.013 to 0.145 mg/m$^3$) within the low concentration of inhalable wood dust (geometric mean amounts to 0.882 mg/m$^3$). In this case when the average value of 12.76% respirable particle share in inhalable dust was measured, a correction factor of 1.2 was obtained for determining the mass concentration of TM ash wood floating particles, in a production plant that produces wooden floors (with a circular saw, a four-sided planer, and a machine for making edge profiles). The conversion factor IOM / OF can vary as a function of the particle size distribution. So, the low share of respirable dust in inhalable dust and low IOM mass concentration with great data dissipations, as a specific properties of TM wood dust, can indirectly influence on the conversion factor but quantification of this impact was not reliably determined.

2. The change in the physical and mechanical properties of TM wood has a complex effect on the distribution of very fine particles of chipped TM wood. Consequently, there is a significant effect on the characteristics of aerosols and the determination of occupational exposure of workers at the workspace in TM wood processing.
3. These results aim to contribute to the reliability of the method of measurement to determine the mass concentration of respirable, inhalable, and total TM hardwood dust, especially ash wood.

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## REFERENCES CITED

Aro, M. D., Geerts, S. M., French, S., and Cai, M. (2019). “Particle size analysis of airborne wood dust produced from sawing thermally modified wood,” *European Journal of Wood and Wood Products* 77, 211-218. DOI:10.1007/s00107-019-01385-z

Barcík, Š., and Gašparík, M. (2014). “Effect of tool and milling parameters on the size distribution of splinters of planed native and thermally modified beech wood,” *BioResources* 9(1), 1346-1360. DOI:10.15376/biores.9.1.1346-1360

Beljo Lučić, R., Kos, A., Antonović, A., Vujasinović, E., and Šimičić, I. (2005). “Properties of chipped wood generated during mechanical wood processing,” *Drvna Industrija* 56(1), 11-19.

Beljo Lučić, R., Čavlović, A., Đukić, I., Jug, M., Ištvanić, J., and Škaljić, N. (2009). “Features of mechanical processing of thermally modified beech wood,” in: *Proceedings of the Wood is Good - New Materials, Quality and Design of Products Conference*, Zagreb, Croatia, pp. 113-121.

CEN/TR 15230 (2005). "Workplace atmospheres – Guidance for sampling of inhalable, thoracic and respirable aerosol fractions," Comité Européen de Normalisation (CEN), European Union, Brussels, Belgium.
Čavlović, A., Beljo Lučić, R., Bešlić, I., Jug, M., and Ištvanić, J. (2009). "Correction factor for real-time determination of wood dust mass concentration by the photometric method," *Drvna Industrija* 60(1), 33-42.
Čavlović, A. O., Beljo Lučić, R., Jug, M., Radmanović, K., and Bešlić, I. (2013). "Side-by-side determination of workers' exposure to wood dust with IOM and open-faced samplers," *Arhiv za Higijenu Rada i Toksikologiju* 64(3), 379-384. DOI: 10.2478/10004-1254-64-2013-2316
Čavlović, A. O., and Bešlić, I. (2021). "Application of photometry in determining the dust mass concentration of hardwoods," *Wood Research* 66(4), 678-688. DOI: 10.37763/wr.1336-4561/66.4.678688
Čavlović, A. O., Bešlić, I., Pervan, S., Barlović, N., Mikšik, M., Klarić, M., and Prekrat, S. (2022). "Occupational exposure to inhalable and respirable wood dust of pedunculate oak (*Quercus robur* L.) in a furniture factory," *BioResources* 17(4), 5831-5847. DOI:10.15376/biores.17.4.5831-5847
Dado, M., Mikusova, L., Hnilica, R., and Oĉkajova, A. (2017). "Calibration of photometer-based direct-reading aerosol monitors," *MM Science Journal* 10(5), 2069-2072. DOI: 10.17973/MMSJ.2017_12_201788
Davies, H. W., Teschke, K., and Demers, P. A. (1999). "A field comparison of inhalable and thoracic size selective sampling techniques," *The Annals of Occupational Hygiene* 43, 381-392.
Dolny, S., Grocki, W., and Rogoziński, T. (2011). "Properties of waste from the cutting of thermally modified oak wood," *Acta Scientarum Polonorum - Silvarum Colendarum Ratio et Industria Lignaria* 10(1), 11-18.
Dzurenda, L., Orlowski, K., and Grzeskiewicz, M. (2010). "Effect of thermal modification of oak wood on sawdust granularity," *Drvna Industrija* 61(2), 89-94.
Dzurenda, L., and Orlowski, K. (2011). "The effect of thermal modification of ash wood on granularity and homogeneity of sawdust in the sawing process on a sash gang saw PRW 15-M in view of its technological usefulness," *Drewno* 54(186), 29-37.
EN 481 (1993). "Workplace atmospheres – Size fraction definition for measurement of airborne particles in the workplace," Comité Européen de Normisation (CEN), European Union, Brussels, Belgium.
European Directive (EU) 2017/2398 (2017). "European Directive (EU) No 2017/2398 of 12 December 2017 amending Directive 2004/37/EC on the protection of workers from the risks related to exposure to carcinogens or mutagens at work of the European Parliament and of the Council," European Union, Brussels, Belgium.
Halterman, A., Sousan, S., and Peters, T. M. (2018). "Comparison of respirable mass concentrations measured by a personal dust Monitor and a personal DataRAM to gravimetric measurements," *Annals of Work Exposures and Health* 62(1), 62–71.
Harper, M., and Muller, B. S. (2002). "An evaluation of total and inhalable samplers for the collection of wood dust in three wood products industries," *Journal of Environmental Monitoring* 4, 648-656. DOI: 10.1039/B202857N
Hlásková, L., Rogoziński, T., Dolny, S., Kopecký, Z., and Jedinák, M. (2015). "Content of respirable and inhalable fractions in dust created while sawing beech wood and its modifications," *Drewno* 58(194), 135-146. DOI: 10.12841/wood.1644-3985.096.11

Hursthouse, A., Allan, F., Rowley, L., and Smith, F. (2004). "A pilot study of personal exposure to respirable and inhalable dust during the sanding and sawing of medium density fibreboard (MDF) and soft wood," *International Journal of Environmental Health Research* 14(4), 323-326. DOI: 10.1080/09603120410001725667

Júda, M., Sydor, M., Rogoziński, T., Kučerka, M., Pedzik, M., and Kminiak, R. (2023). "Effect of low-thermal treatment on the particle size distribution in wood dust after milling," *Polymers* 15, article 1059. DOI:10.3390/polym15041059

Kauppinen, T., Vincent, R., Liukkonen, T., Grzebyk, M., Kauppinen, A., Welling, I., Arezes, P., Blacks, N., Bochmann, F., Campelo, F., *et al*. (2006). "Occupational exposure to inhalable wood dust in the member states of the European Union," *The Annals of Occupational Hygiene* 50(6), 549-561. DOI: 10.1093/annhyg/mel013

Kenny, L. C., Aitken, R., Chalmers, C., Fabriès, J. F., Gonzalez- Fernandez, E., Kromhout, H., Lidén, G., Mark, D., Riediger, G., and Prodi, V. (1997). "A collaborative European study of personal inhalable aerosol sampler performance," *The Annals of Occupational Hygiene* 41, 135-153. DOI: 10.1093/annhyg/41.2.135

Koch, W., Dunkhorst, W., and Lödding, H. (1999). "Design and performance of a new personal aerosol monitor," *Aerosol Science and Technology* 31, 231-246.

Koch, W., Dunkhorst, W., Lödding, H., Thomassen, Y., Skaugset, N. P., Nikanov, A., and Vincent, J. (2002). "Evaluation of RespiCon® as a personal inhalable sampler in industrial environments," *Journal for Environmental Monitoring* 4, 657-662.

Kos, A., Beljo Lučić, R., Šega, K., and Rapp, A. (2004). "Influence of woodworking machine cutting parameters on the surrounding air dustiness," *Holz als Roh- und Werkstoff* 62(3), 169-176. DOI: 10.1007/s00107-004-0473-2

Krauss, A., Piernik, M., and Pinkowski, G. (2016). "Cutting power during milling of thermally modified pine wood," *Drvna Industrija* 67(3), 215-222. DOI: 10.5552/drind.2016.1527

Kučerka, M., and Očajková, A. (2018). "Thermowood and granularity of abrasive wood dust," *Acta facultatis xylologiae Zvolen* 60(2), 43-51. DOI:10.17423/afx.2018.60.2.04

Lanki, T., Alm, S., Ruuskanen, J., Janssen, N. A. H., Jantunen, M., and Pekkanen, J. (2002). "Photometrically measured continuous personal PM2.5 exposure: Levels and correlation to a gravimetric method," *Journal of Exposure Analysis and Environmental Epidemiology* 12, 172-178. DOI: 10.1038/sj/jea/7500218

Lidén, G., Melin, B., Lidblom, A., Lindberg, K., and Norén, J. O. (2000). "Personal sampling in parallel with open-face filter cassettes and IOM samplers for inhalable dust – implications for occupational exposure limits," *Applied Occupational and Environmental Hygiene* 15(3), 263-276. DOI: 10.1080/104732200301584 21

NIOSH (1998). "Method 0600," in: *Manual of Analytical Methods*, National Institute for Occupational Safety and Health, Center for Disease Control and Prevention, Washington, D.C., USA.

Notø, H. P., Nordby Karl-Christian, and Wijnand Eduard (2016). "Relationships between personal measurements of 'Total' dust, respirable, thoracic, and inhalable aerosol fractions in the cement production industry," *The Annals of Occupational Hygiene* 60(4), 453-466. DOI: 10.1093/annhyg/mev093

Mikušová, L., Očajková, A., Dado, M., Kučera, M., and Danihelová, Z. (2019). "Thermal treatments effect on dust emission during sanding of meranti wood," *BioResources* 14(3), 5316-5326. DOI: 10.15376/biores.14.3.5316-5326

Muranko, H. J., Hethmon, T.A., and Smith, R. G. (2001). “Total” and respirable dust exposures in the U.S. carbon black manufacturing industry,” *American Industrial Hygiene Association Journal* 6(1), 57-64. DOI: 10.1080/15298660108984610

Očkajová, A., Barcík, Š., Kučerka, M., Koleda, P., Korčok, M., and Vyhnáliková, Z. (2019). “Wood dust granular analysis in the sanding process of thermally modified wood *versus* its density,” *BioResources* 14(4), 8559-8572. DOI: 10.15376/biores.14.4.8559-8572

Očkajová, A., Kučerka, M., Kminiak, R., Krišťák, L., Igaz, R., and Réh, R. (2020). “Occupational exposure to dust produced when milling thermally modified wood,” *International Journal of Environmental Research and Public Health* 17, 1478-1492. DOI: 10.3390/ijerph17051478

O'Shaughnessy, P. T., and Slagley, J. M. (2002). “Photometer response determination based on aerosol physical characteristics,” *American Industrial Hygiene Association Journal* 63(5), 578-585. DOI: 10.1080/15428110208984743

Pervan, S. (2009). *Tehnologija Obrade Drva Vodenom Parom [Water Vapor Wood Processing Technology]*, Faculty of Forestry and Wood Technology, Zagreb, Croatia.

Piernik, M., Rogoziński, T., Krauss, A., and Pinkowski, G. (2018). “The influence of the thermal modification of pine (*Pinus sylvestris* L.) wood on the creation of fine dust particles in plane milling,” *Journal of Occupational Health* 61, 481-488. DOI: 10.1002/1348- 9585.12075

Predicala, B. Z., and Maghirang, R. G. (2003). “Field comparison of inhalable and total dust sampler for assessing airborne dust in swine confinement barns,” *Applied Occupational and Environmental Hygiene* 18, 694- 701. DOI: 10.1080/10473220301375

Rando, R., Poovey, H., Mokadam, D., Brisolara, J., and Glindmeyer, H. (2005a). “Field performance of the RespiConTM for size-selective sampling of industrial wood processing dust,” *Journal of Occupational and Environmental Hygiene* 2(4), 219-226. DOI: 10.1080/15459620590930309

Rando, R. J., Gibson, R. A., Kwon, C. W., Poovey, H. G., and Glindmeyer, H. W. (2005b). “On-filter determination of collected wood dust by diffuse infrared Fourier-transform spectroscopy (DRIFTS),” *Journal of Environmental Monitoring* 7(7), 675 – 680. DOI: 10.1039/B502025E

Ratnasingam, J., and Ioras, F. (2012). “Effect of heat treatment on the machining and other properties of rubberwood,” *European Journal of Wood and Wood Products* 70(5), 759-761. DOI: 10.1007/s00107-011-0587-2

Sass-Kortsak, A. M., Holness, D. L., Pilger, C. W., and Nethercott, J. R. (1986). “Wood dust and formaldehyde exposures in the cabinet-making industry,” *American Industrial Hygiene Association Journal* 47(12), 747-753. DOI: 10.1080/15298668691390601

Szewczyńska, M., and Pośniak, M. (2017). “Assessment of occupational exposure to wood dust in the Polish furniture industry,” *Medycyna Pracy* 68(1), 45-60. DOI: 10.13075/mp.5893.00458

Tatum, V. L., Ray, A. E., and Rovell-Rixx, D. C. (2001). “The performance of personal inhalable dust samplers in wood-products industry facilities,” *Applied Occupational and Environmental Hygiene* 16(7), 763-769. DOI: 10.1080/10473220121612

Tatum, V., Ray, A. E., and Rovell-Rixx, D. (2002). “Performance of the RespiCon personal aerosol sampler in forest products industry workplaces,” *American*

*Industrial Hygiene Association Journal* 63(3), 311-316. DOI: 10.1080/15428110208984719
Thomas, A., and Gebhart, J. (1994). "Correlation between gravimetry and light-scattering photometry for atmospheric aerosols," *Atmospheric Environment* 28(5), 935-938. DOI: 10.1016/1352-2310(94)90251-8
Thorpe, A., and Walsh, P. T. (2007). "Comparison of portable, real-time dust monitors sampling actively, with size-selective adaptors, and passively," *The Annals of Occupational Hygiene* 51(8), 679-691. DOI: 10.1093/annhyg/mem047
Thorpe, A., and Walsh, P. T. (2013). "Direct-reading inhalable dust monitoring. An assessment of current measurement methods," *The Annals of Occupational Hygiene* 57(7), 824-841. DOI: 10.1093/annhyg/met002
Vaughan, N. P., Chalmers, C. P., and Botham, R. A. (1990). "Field comparison of personal samplers for inhalable dust," *The Annals of Occupational Hygiene* 34(6), 553-173. DOI: 10.1093/annhyg/34.6.553
ZH 1/120.41(1989). "Verfahren zur Bestimmung von Holzstaub [A method for the determination of wood dust]," Zentralstelle für Unfallverhütung und Arbeitsmedezin-Hauptverband der gewerblichen Berufsgenossenschaften [Central Office for Risk Prevention and Occupational Medicine-Confederation of Professional Trade Associations], Carl Heymans Verlag KG, Köln, Germany.

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