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APPLICATION OF PHOTOMETRY IN DETERMINING THE DUST MASS CONCENTRATION OF HARDWOODS

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ABSTRACT

Given the carcinogenicity of hardwood dust, the aim of this study was to determine the effectiveness of the photometric method for different types of woodworking machines and its application in determining the mass concentration of inhalable dust for raw and dry hardwoods. In addition to the optical part of the device, the input part of the measuring device contains the Institute of Occupational Medicine (IOM) inhalable dust filter holder. This correlation of gravimetric and photometric methods in determining the dust mass concentration showed that photometry underestimates the mass concentration measured gravimetrically. The results of this study recommend the application of a correction factor 2 for a timber band saw and a correction factor 3 for circular saws in determining the mass concentration of hardwood dust by the photometric method. It was showed that photometry can be used if the correction factor of the optical device has been previously tested for specific wood processing place.

KEYWORDS: Photometry, correction factor, inhalable dust, hardwoods, carcinogenicity.

INTRODUCTION

In 1994 IARC (International Agency for Cancer Research) researchers classified wood dust into the first group of carcinogenic substances and they found that higher risk was caused by hardwood dust than by softwood dust (Kos et al. 2004). Based on many scientific researches of professional diseases and classifications of the IARC in 1999 the European Union declared wood dust as carcinogenic substances (Klein et al. 2001, Kauppinen et al. 2006, Llorente et al. 2009, Douwes et al. 2017, Holm and Festa 2019). Latest European Directive 2017/2398 on the protection of workers from the risks related to exposure to carcinogens or mutagens at work prescribe the limit values of 2 $mg \cdot m^{-3}$ (3 $mg \cdot m^{-3}$ until 17 January 2023) which refer to mass concentration of inhalable dust of hardwood species measured or calculated in relation to a reference period of 8-hour exposure of workers. Since 1999, many EU countries have applied a lower exposure limit to wood dust than the prescribed EU Directive (Spee et al. 2006, Campopiano et al. 2016).

Many authors have investigated the possibility of applying photometry as a real-time method that lasts shorter than working shift, in addition to the most reliable application of the gravimetric method for determining the mass concentration of wood dust in worker exposure studies (Koch et al. 1999, Koch et al. 2002, Tatum et al. 2002, Rando et al. 2005a,b). The mentioned authors presented the development and application of the RespiCon (TSI, Inc.) optical device, with the simultaneous selective collection of the inhalable, thoracic and respirable fraction of floating particles. The advantage of measuring worker exposure with a direct reading monitor is that it allows graphical display of worker activity and identification of peak exposure and underlying determinants in real time (Rosén et al. 2005). Continuous optical measurement provides detailed information on personal exposure and real-time work tasks, secondary sources and specific worker behaviors. The mass concentration of inhalable wood dust in full shift was determined by a video exposure monitoring system that includes video cameras, a real-time Split2 dust monitor connected to an IOM sampling head (Douwes et al. 2017). Thorpe and Walsh (2007) were compared the optical instruments' responses of the Split2 (SKC Ltd) and Microdust Pro (Casella Ltd) with the reference IOM inhalable dust samplers. The conical inhalable filter holder (CIS) and IOM inhalable filter holder with porous foam inserts were tested as optical device inlet adaptor. Measurements using the Split2 with IOM adaptor showed better agreement with the reference IOM inhalable dust sampler compared to the Microdust Pro device with CIS inlet adaptor. The main difference between IOM and CIS samples is in the size and shape of the orifices and the concentration measurements showed larger differences for larger particles in laboratory tests and field research (Campopiano et al. 2016). Baltrenas and Kvasaukas (2005) using Microdust Pro optical method determined 4,6% higher values of wood dust mass concentration by than gravimetric method. Thorpe and Walsh (2013) concluded that in order 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. The optical device uses the principle of near-forward light scattering of an infrared radiation to immediately and continuously measure the concentration in $mg \cdot m^{-3}$ of airborne dust particles. As the particle passes between the lenses, the light intensity decreases, and an output signal proportional to the value of the mass concentration of suspended particles from the working atmosphere is recorded. In order to determine the predictable correction factor for different levels of dust concentration related to photometric and gravimetric measurements of wood dust, the sensitivity of the photometer in relation to the particle size distribution, particle density and its refractive index was analysed (O'Shaughnessy et al. 2002, Dado et al. 2017). A significant influence of the relative humidity of the surrounding air on the results of the photometric method was also observed (Thomas and Gerbhart 1994, Lanki et al. 2002). The density of wood particles varies depending on the species of wood and the moisture content in the wood, but also the shape and size of the particles due to the mechanical processing in which they are formed. Therefore, photometer mass concentration measurements additionally require an assessment of the effectiveness in a specific wood environment. According to theoretical predictions, previous studies have shown lower photometry efficiency at higher mass concentrations of inhalable dust (Čavlović et al. 2009). This is supported by the results of research that increasing the mass concentration of total particles does not increase proportionally and the mass fraction of respirable particles (Kos et al. 2004). In this regard, it is known complete photometric and gravimetric stacking results (correction factor of about 1) for particles up to 10 μm. The best photometer sensitivity for particles of 0.6 μm was found at constant mass concentration (Čavlović et al. 2009).

The correction factor for any type of aerosol is determined from the ratio of mass concentrations measured by the gravimetric method and mass concentrations measured by infrared radiation during photometer measurements (NIOSH Manual for analytical methods). The correction factor needs to be calculated due to the influence of the physical properties of the particles (type and size of the particles, refractive indexes and light scattering properties of particles) on the sampling efficiency. However, previous studies of dust exposure at workplace have shown that other influencing factors need to be taken into account and that the type of wood machining has a significantly greater impact on the mass concentration than the wood species and the quality of exhaustion (Kos et al. 2002). The authors Palmqvist and Gustafsson (1999) analysed the influencing factors on the emission of wood dust, namely the influence of mechanical processing (average chip thickness and rake angle) and the influence of wood properties (moister content in wood and the wood fibers direction). It has been shown that the average chip thickness of sawdust has the greatest influence (fi = -5.7) on the emission of particles into the surrounding air, while the moisture content in wood has a significantly smaller impact (fi = -2.0). In other studies of wood dust emissions from different working machines, the reduction of the average chip thickness significantly increased the wood dust emissions in the working environment (Kos et al. 2004). The aim of this research was to determine the efficiency of the photometric method by obtaining a correction factor for different types of woodworking machines and its application in determining the mass concentration of inhalable dust for raw and dry hardwood (beech and oak wood).

MATERIAL AND METHODS

Determination of wood dust mass concentration by photometric and gravimetric method was made at different wood machining places, during processing raw and dry hardwood species (oak and beech wood) in sawmill (band saw and circular saw) and in wooden floor production plant (four side planer and circular saw). The optical device the Split2 model manufactured by SKC (Dorset, UK, 2006), for continuous measurement of mass concentration of floating particles, consists of a device for data processing and a display, an input part consists of the inhalable dust IOM filter holder and an optical part of the device (Fig. 1).

The optical part of the device uses an infrared light source located at an angle of 90° to the photodetector. The optical device operated actively connected to a Casella pump (Bedford, UK, 2001), set to an air flow of 2 l·min^{-1} (EN ISO 10882-1: 2001). The air sample passes through an optical detector (photometric) and then through a filter holder (gravimetric). The correction factor for continuous determination of mass concentration was obtained as the ratio of mass concentration determined by gravimetric and photometric methods.

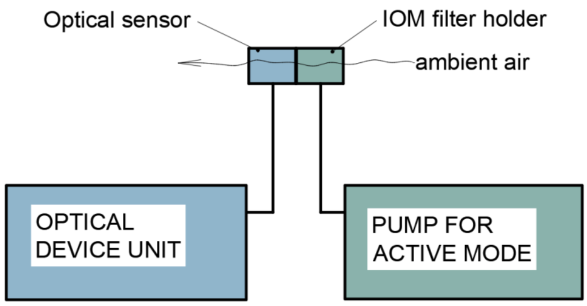

Fig. 1: Optical device connected to the pump and optical input part with IOM filter holder.

The instructions of NMAM Method 0600 (NIOSH Manual of analytical methods, National Institute for Occupational Safety and Health) were applied in calibration of device for continuous determination of mass concentration. Conducting continuous measurements for at least 30 min is a condition for determining short-term exposure. Wood dust samples were collected on average 40 min in dry wood processing and 110 min in raw wood processing. To achieve the reliability of continuous measurement with this device, the correction factor is determined from the mean value obtained from at least10 repetitions.

The mass concentration of inhalable dust was determined by gravimetric method (according to the standard ZH 1/120.41: 1989). The 25 mm quartz filters (Whatman QM-A) were conditioned in the desiccator on (20 ± 1) °C and (50 ± 5)% relative humidity 24 h before and after weighing and before and after the sampling. The weighing was carried out on a micro scale, type METTLER-TOLEDO MX-5 (Greifensee, Switzerland), which is capable of reading values at 10^{-6}, with the measuring deviation of 10^{-4} g. The stationary method of collecting samples was chosen due to the required precision of the optical part of the very sensitive device. HRN CEN /TR 15230: 2007 states that it is possible to use personal samplers for stationary collection.

Statistical differences in correction factors between samples obtained during processing with different machines were tested by the Student's test. The Mann-Whithey u-test was used when the condition of homogeneity of variance was not fulfilled. Descriptive statistics of variables and statistical analyses were performed using statistical software - STATISTICA 13.4.0.14.

RESULTS AND DISCUSSION

The arithmetic average values of calculated correction factor for different woodworking machines, timber band saw, circular saw and four side planer, from the results of determining the mass concentration of inhalable wood dust by gravimetric and photometric method, are shown in Tab. 1. The geometric mean as a better indicator of dust emission was selected to show the average values of the wood dust mass concentration for all group of samples.

Tab. 1: Gravimetrically and photometrically determined mass concentration of inhalable dust and correction factors.

Wood processing machine	**Wood dust**	**Number of samples**	**Mass concentration**[a], ($mg \cdot m^{-3}$)		**Correction factor**[b], c_g/c_{ph}
			Gravimetric method, c_g	**Photometric method, c_{ph}**	
Timber band saw	Raw oak wood	10	0.818	0.502	2.24 ± 1.35
	Raw beech wood	13	0.661	0.442	1.84 ± 1.16
Circular saw	Raw oak wood	11	0.962	0.344	3.18 ± 1.45
	Dry beech wood	11	0.171	0.093	2.88 ± 2.37
Four side planer	Dry oak wood	13	0.754	0.314	3.10 ± 1.96
	Dry beech wood	10	3.297	1.052	3.74 ± 1.89

a - geometric mean; b - arithmetic mean and standard deviation.

From the range of the mean values of the correction factors for individual machine types it is obviously that it is not enough to distinguish correction factors according to the wood species, entirely. The obtained correction factors represent the low efficiency of the photometric method which underestimates the mass concentrations values obtained gravimetrically. Stacking the measured values by the two methods, photometric and gravimetric, shown in Fig. 2.

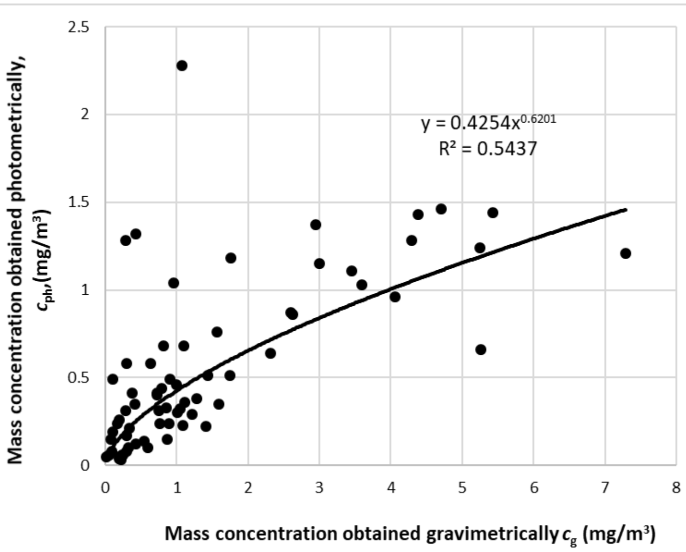

Fig. 2: Correlation of mass concentrations obtained by gravimetric method and photometric method.

The use of photometry is reliable only with a predefined correction factor for a particular case of work working place due to the weakness of the regression model with a low coefficient of determination (R^2 = 0.54). Strong linear relationships (R^2 = 0.95 ÷ 0.99) were observed between mass concentrations of some other aerosol (diesel exhaust fume, welding fume, Arizona road dust ARD, and salt aerosol) measured photometrically and gravimetrically (Halterman et al. 2018). Aerosol type strongly influence sensor response, indicating the need for on-site calibration to convert sensor output to mass concentration. Once calibrated, however, the mass concentration estimated with low-cost sensors was highly correlated with that of reference instruments (Sousan et al. 2016).

In laboratory conditions at high concentrations (30-50 $mg \cdot m^{-3}$) the same model of optical device (Split2) also underestimates the gravimetrically obtained concentration of inhalable pine dust by an average of 32% (Thorpe 2007). An improvement in the measurement of Split2 compared to the reference IOM collector was obtained by redesigning the filter holder by SKC to improve the internal seals inside the sampler after it was determined that the previous design allowed dust around the backup filter (Thorpe and Walsh 2007).

Pearson correlation test of all measured values obtained by two measuring methods has shown medium strong correlation (k = 0.7). In two cases only, circular saw/raw oak wood dust and four side planer/dry oak wood dust, were found a very strong positive correlation between the mass concentration values measured by two methods (k = 0.8 and k = 0.9, resp.). This contributes to the high reliability of the test results in these cases, in which the efficiency of photometry is among the lowest and correction factor amounts 3.18 and 3.1, respectively.

Statistical results from Tab. 2 have shown that the correction factors for two types of wood species do not differ significantly for timber band saw, circular saw and four side planer. At the same working places, the gravimetrically obtained mass concentration of beech and oak wood dust significantly do not differ for the timber band saw, only (Tab. 3). There is the most significant difference ($p = 0$) of mass concentration measured gravimetrically near circular saw when processing raw and dry hardwood, in spite of the correction factor for the same cases with no significant difference.

Tab. 2: Comparison of correction factors for oak- and beech- wood dust.

Wood processing machine	Wood dust	Number of samples	Homogeneity of variances test		t-test
			F	p	p
Timber band saw	Raw oak wood	10	1.357	$p > 0.05$	**0.61**
	Raw beech wood	13			
Circular saw	Raw oak wood	11	2.666		**0.14**
	Dry beech wood	11			
Four side planer	Dry oak wood	13	1.073		**0.94**
	Dry beech wood	10			

F- test of variance; p-significant level.

Tab. 3: Comparison of gravimetrically determined mass concentrations near wood processing machines with respect to the type of wood dust.

Wood processing machine	Wood dust	Number of samples	Homogeneity of variances test		t-test	u-test
			F	p	p	p
Timber band saw	Raw oak wood	10	4.633	$p < 0.05$	-	**0.55**
	Raw beech wood	13				

Circular saw	Raw oak wood	11	24.91		-	**0.001**
	Dry beech wood	11				
Four side planer	Dry oak wood	13	2.144	p > 0.05	**0.044**	-
	Dry beech wood	10				

F- test of variance; p-significant level.

Statistical testing showed a significant difference between the correction factors for a timber band saw and a four side planer (Tab. 4). The mass concentration measured by the gravimetric method near woodworking machines differs significantly between a timber band saw and a four side planer and between a circular saw and a four side planer (Tab. 5).

Tab. 4: Comparison of correction factors for wood processing machines.

Wood processing machine	**Number of samples**	**Homogeneity of variances test**		**t-test**	**u-test**
		F	**p**	**p**	**p**
Timber band saw – Circular saw	23/22	2.430	p < 0.05	-	**0.09**
Timber band saw - Four side planer	23/23	2.403		-	**0.02**
Circular saw - Four side planer	22/23	1.011	p > 0.05	**0.54**	-

F- test of variance; p-significant level.

Tab. 5: Comparison of gravimetrically determined mass concentrations of wood dust measured next to woodworking machines.

Wood processing machine	**Number of samples**	**Homogeneity of variances test**		**t-test**	**u-test**
		F	**p**	**p**	**p**
Timber band saw – Circular saw	23/22	1.101	p > 0.05	**0.28**	-
Timber band saw - Four side planer	23/23	12.907	p < 0.05	-	**0.03**
Circular saw - Four side planer	22/23	11.729		-	**0.002**

F- test of variance; p-significant level.

According to the mean values of the correction factor from the diagram in Fig. 3, for photometric measurements of hardwood dust mass concentration, the use of value 2 as a correction factor for a timber band saw and value 3 as a correction factor for a circular saw can be suggested. Therefore, the correction factor 3.4 can be used for the photometric determination of the dust mass concentration of hardwoods next to the four side planer.

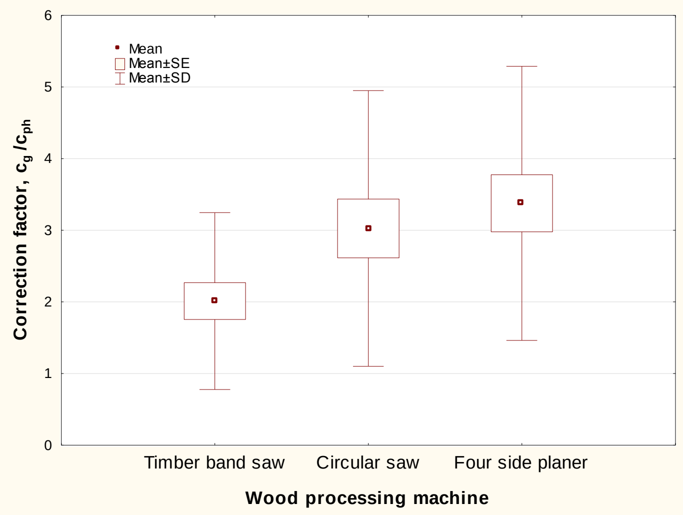

Fig. 3: Distribution diagram of mean values and data dissipation of correction factor for wood processing machines (SD-standard deviation, SE- standard error of mean).

In previous studies of the correction factor by type of wood, the lowest values are 1.0 for raw fir wood, and the highest 3.74 for dry oak wood dust (Čavlović et al. 2009). It is possible that, in addition to the mass concentration, the efficiency of photometry is influenced by other factors, the moisture content in the wood and the content of fine particles in the inhalable dust. In general, the efficiency of the photometric method decreased with increasing aerodynamic particle diameter (Koch et al. 1999, Koch et al. 2002, Tatum et al. 2002, Rando et al. 2005a,b). Authors Palmqvist and Gustafsson (1999) found that dust emissions from woodworking machine operation increase by reducing the average chip thickness and by reducing the moisture content of the wood material. The average thickness of the chips produced from a circular saw is smaller than the average thickness of the chips from a band saw (Kos et al. 2004). The particle size distribution in chipped beech wood material shows that the proportion of the smallest particles (less than 0.09 mm) formed on a four-sided planer is twice less than the proportion of the smallest particles formed on a circular saw and nine times less than the proportion of the smallest particles formed on a band saw (Beljo Lučić et al. 2005). In this regard, a model for estimation of percentage fraction of fine dust mass as a function of chip thickness was found (Rautio et al. 2007).

CONCLUSIONS

Determining the correction factor for using a photometric method to determine the mass concentration of wood dust is very complex due to many influencing factors on the efficiency of the optical device. This study showed that the efficiency of measuring the mass concentration of wood dust by photometry depends not only on the type of wood, but also on the type of processing. The research resulted in the obtained correction factors and suggested for application in determining the mass concentration of inhalable dust near timber band saw (c_g/c_{ph} = 2), circular saw (c_g/c_{ph} = 3) and four side planer (c_g/c_{ph} = 3.4). This indicates that photometry regularly underestimates the mass concentration measured gravimetrically.

In this case, in determining of dry and wet hardwood dust mass concentration, the strength of the optical device correction factor estimation model is small (R^2=0.54). In practice, the correction factor for an optical device should be defined on a case-by-case basis, taking into account the wood species and moisture content of the wood, the type of mechanical wood treatment and the quality of the exhaust devices.

The photometric method of continuous determination of mass concentration can be a useful method for detecting incidental levels of mass concentrations of wood dust, because wood processing workers in the Republic of Croatia should be additionally protected from exposure to hardwood dust, due to the participation of beech and oak in processing up to 65%.

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