Evaluation of African Padauk (*Pterocarpus soyauxii*) Explosion Dust

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The article describes the granulometric analysis of airborne wood dust of African padauk (*Pterocarpus soyauxii*). Sandpaper was used under industrial relevant conditions to generate wood dust with a relatively wide particle size distribution (<63, 63, 71, 100, 200, 315, or 500 µm). This article aimed to perform a sieve analysis of the wood dust of African Padauk, characterize its morphological structure, determine certain physical properties (density, bulk density, and moisture content), and assess the effect of airborne dust particle size on minimum ignition temperatures. The 100-µm fraction was the most frequent dust particle size and represented 42.14 ± 1.049%. The ignition temperature of airborne dust was 390 °C for the 500-µm fraction and 370 °C for the 71-µm fraction.

Keywords: African padauk; Dust; Granulometry; Morphology; Ignition temperature

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INTRODUCTION

Dust can be defined as small particles in the atmosphere settling under their own weight that may remain scattered in the air for some time (EN 50281-2-1 1999; WHO 1999). The term generally includes ground solid substances referred to as powder, flour, fiber fragments, and so on (Marková and Očkajová 2018). In general, the particle size is defined by two dimensional parameters (that are significantly larger than the third) that are both smaller than 500 µm (EN 14034-1:2004+A1 2011). Wood dust, as a by-product of wood mechanical processing or treatment of wood, especially the grinding of wood (Očkajová *et al.* 2006, 2014; Dzurenda *et al.* 2010; Dzurenda and Orlowski 2011; Očkajová and Banski 2013; Mračková *et al.* 2016), plays a negative role with respect to risk of fire (Kovshov *et al.* 2015; Rohr *et al.* 2015) or explosion (Amyotte and Eckhoff 2010; Amyotte 2013; Rogoziński and Očkajová 2013; Žigo *et al.* 2014; Krentowski 2015; Loveček *et al.* 2016).

The assessment of wood dust depends on its origin, characteristics, size of the dust particles, its concentration in the air, the length and conditions of its action, and an individual's sensitivity to dust (Lighty *et al.* 2000; Rohr *et al.* 2015). Wood dust, which is produced mainly during grinding, is highly flammable and may form an explosive mixture with air in certain circumstances (Saejiw *et al.* 2011). The dust of some hardwoods (beech, oak) has been designated as a category 1 carcinogen, with its inhalation most often causing cancer of beneficial cavities (Požgaj *et al.* 1997).

The negative effect of wood dust relates to the size of the particles. It is necessary to know its granulometric composition, which is the number or weight number of particle in a certain range (Marková *et al.* 2016). Bigger dust fractions tend to settle (Tureková *et al.* 2005; Tureková 2009; Marková *et al.* 2018). The presence of micro-fractions (< 100 μm) promotes the formation of airborne dust. Polydispersed dust consists of particles of different sizes and is formed in the processed wood production (Očkajová and Banski 2013; Marková and Očkajová 2018). A granulometric analysis of dust determines the pulverization level of the rural wood material, representing one of the characteristic features of dust that creates a dispersive system (Mračková *et al.* 2016). The fraction range is determined by mesh sizes. Particles that can pass through a sieve of a given mesh size or be retained on the sieve with smaller openings fall into the fraction range determined by both mesh sizes. A collection of particles of different sizes is created through sieving. Based on sieving procedure, the cumulative grain size distribution curve is created (Dzurenda and Orlowski 2011).

Dust is present in woodworking environments in its settled form as well as in its airborne form. The two forms can change from one to another quite easily, *e.g.*, by vibrations, shocks, or air flow (Kasalová and Balog 2011; Martinka and Rantuch 2013). Thus, the fire hazard of wood dust depends on its form. Settled wood dust tends to self-ignite and flamelessly burn (smoldering). Flameless burning, or smoldering, is dangerous due to the large quantities of the combustion products present, in particular carbon monoxide, throughout the burning process. From a fire safety perspective, airborne dust is the most dangerous type of dust because of it can be potential source of an explosion if optimal fire conditions exist: dispersed dust, sufficient air-oxygen, and a sufficiently strong ignition source (Martinka and Rantuch 2013; Martinka *et al.* 2014). Airborne flammable dust is able to rapidly respond to oxidative stress. This response has the nature of an explosion under certain conditions, which ultimately can lead to detonation (Marková and Očkajová 2016; Marková and Očkajová 2018). Another significant but undesirable effect is the impact of wood dust on human health (Tian *et al.* 2007; Top *et al.* 2016).

Ignition temperature is the key parameter evaluating the risk of airborne dust initiation. It is monitored in a standardized test apparatus (ceramic tube furnace), in line with EN 50281-2-1 (2002), where the airborne wood dust sample is exposed to radiation heat with the given ambient temperature. The ignition temperature of airborne dust is the lowest temperature of the innermost wall of the tube furnace, where the ignition of the airborne dust occurs in the air inside the tube furnace (Marková and Očkajová 2018).

Because of its beautiful and unusual color and patterns, African padauk is used in the production of flooring, furniture, and interior decorations (Van Gemerden *et al.* 2003; Čarodreva 2019; Vidholdová and Reinprecht 2019). It has a unique reddish orange color, and the wood is sometimes referred to by the name of vermillion. Unfortunately, this dramatic color will darken and become reddish brown in color as a result of external effects (especially air humidity) and aging. Padauk is moderately heavy, strong, and stiff with exceptional stability. It is a popular hardwood among hobbyist woodworkers because of its unique color (Fan *et al.* 2012).

In comparison with European tree species, tropical tree species are more invariable due to higher relative air humidity and more stable climatic conditions. Tropical wood species are more homogeneous (not such a noticeable difference between summer and spring wood) than European tree species (Vigué 2006). Tropical wood is of higher density and hardness and has greater resistance to wear (Reinprecht *et al.* 2012; Nice Decor 2017). Tropical tree species have a greater lifespan and are suitable for wet environments. Therefore, tropical timber is often used in exteriors such as terrace flooring, tables, chairs, pool lining, *etc*. (Nice Decor 2017).

Reinprecht *et al.* (2012) evaluated tropical tree species as wood types with a great resistance against biological agents and mechanical wear. They have good dimensional stability and nice aesthetics. The wood is commonly used for outer structures, cladding, veneer, garden furniture, or special plywood. The prevalence of tropical tree species in woodworking brings some problems in the presence of wood dust. According to several references in manual of Hausen (1981), Padauk species have been suspected as health hazards (Hausen, 1981).

As first-class furniture and cabinet wood, padauk also makes fine carvings (Tchinda *et al.* 2014), and musical instruments (Brémaud *et al.* 2011; Straze *et al.* 2015). Because it has high resistance to abrasion, great strength, and it does not readily decay, it adapts well to cutting board stock (Fan *et al.* 2012). African padauk is mainly used in carpentry (exterior or interior), in particular in more humid environments (Bernard *et al.* 2018).

The aim of this research was to analyze and compare the granulometric structure of wood sanding dust from African padauk prepared by hand grinder, identify its morphological structure, determine the given physical properties (average bulk density and dust moisture). The focus was on microfractions (particles with a diameter of ≤100 µm) and the impact assessment particle size (particle size <100µm) on the minimum ignition temperatures of airborne dust.

EXPERIMENTAL

Materials and Methods

The samples of African padauk (131 × 50 × 20 mm^3) were dried to the moisture content of approximately 8-10%. They were made in a woodworking shop owned by a private company that manufactures interior elements based in Žilina (Slovakia) by a wood cutting saw (CNC Panel Saw Machine, Shandong, China) (Table 1).

Table 1. Padauk Sample Used in the Experiment

Sample	Common Name[1]	Scientific Name	Density at MC 12%	
			Value (kg/m^3)	Reference
Fabaceae	Padauk	*Pterocarpus soyauxii*	650 to 850	Wagenführ *et al.* (2007)
			647	Vidholdova and Reiprecht (2019)
Visual			590	Jankowska (2018)
			790	Data Scheet Padouk (2012)
			720.40 ± 9.52	Current study

Notes: [1]Association Technique Internationale des Bois Tropicaux (ATIBT) in France; MC- moisture content

Wood dust samples - Preparation process

The samples were sanded using a Makita 9556CR 1400W disc sander (Makita Numazu Corp., Romania) and K36 sandpaper (Topex, Kinekus, Žilina, Slovakia) to obtain homogeneous dust particles. The samples were prepared by an expert on grinding to make the process as realistic as possible considering certain important factors such as the pressure against the surface of the fragment, the grinding speed, as well as the direction of the sanding (across the wood grain). The grinding was completed in Experimental laboratory at the Department of Fire Engineering of the Faculty of Safety Engineering in Žilina (Slovakia). The dust was collected in the hopper and poured into a hermetically sealed glass container to prevent the dust from absorbing any moisture. The hopper was cleaned after each grinding and the process was repeated three times. A total of 300 g of dust was collected from each board of padouk (collection three boards), serving as a basis for the granulometric analysis.

Physical properties of wood dusts and sieve analysis

The moisture level of the wood samples was determined using granulometric analysis according to STN 49 0108 (1993). The sieve analysis was made on the vibration sieve machine (Retsch AS 200 control; Retsch GmbH, Haan, Germany) and the bulk density of wood dusts according to ISO 23145-1 (2007) (Table 1). Sieve analysis was conducted on a Retsch AS 200 sieve shaker vibration machine (Retsch AS 200 control, Retsch GmbH, Haan, Germany) in line with ISO 3310-1 (2007). The bag was cleaned after each tree specimen using an industrial vacuum cleaner (ETA - Slovakia, spol. s.r.o., Bratislava, Slovakia). For the sieve analysis, each type of wood dust was divided into seven fraction sizes (500, 315, 200, 100, 71, 63, and < 63 μm). The sieves together with the wood dust were weighed 30 g using laboratory scales with the readability of 0.001 g. The measurement procedure was performed five times, for 10 min. Wood dust moisture testing was carried out according to STN EN 13183-1 in a hot-air oven at a temperature of 103 ± 2 ° C for 24 hours.

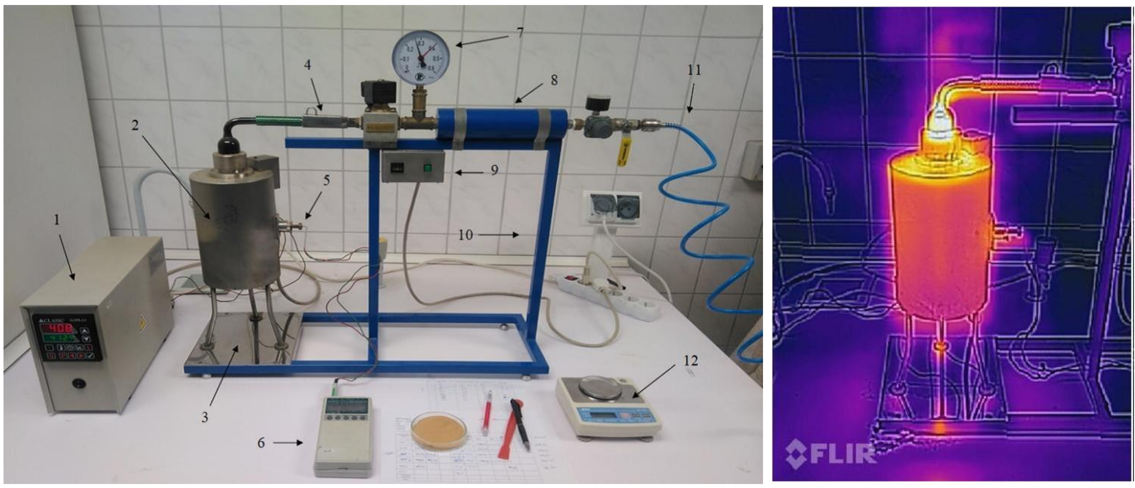
Shape and size of wood dust particles

Wood and its structure can be observed at macroscopic and microscopic levels (Humulák 2019). The shape and the size of wood dust particles were determined *via* microscopic analysis using a Nikon Eclipse Ni (Nikon Corp., Tokyo, Japan) with a Nikon DS-Fi2 camera (Nikon Instruments Inc., Melville, NY, USA). Super wide field microscopy systems, such as the microscope the Eclipse Ni-E (Nikon Corp., Tokyo, Japan), increase the viewable field area (Goldsberry *et al.* 2014; Furukawa 2016). An Eclipse Ni-E (Nikon Corp., Tokyo, Japan) microscope was used. This microscope has an electric XY stage and two c-mount camera ports. This is the basic configuration for the bright field observation of this microscope. One camera port is used for the Nikon DS-Fi2 (Nikon Instruments Inc., Melville, NY, USA) 2560 × 1920 pixels full-HD colour camera, and the other was for fluorescent observation. The Nikon DS-Fi2 camera was connected to the computer by a USB cable and used for obtaining the image. Microscopic analyses of wood dusts were made for the 71 μm fraction.

The wood dust structure was observed under a Nikon SMZ 1270 stereomicroscope (Nikon Corp., Beijing, China). Stereomicroscopic analysis was completed at the Institute of Research in Banská Bystrica, Slovakia. The SMZ 1270 (Nikon Corp., Beijing, China) are universal research microscopes providing the best in their class magnification range. With a 12.7: 1 zoom head, the magnification range is 0.63× to 8×. The total range of microscope magnifications, with additional equipment, ranged from 3.15× to 480×. Stereomicroscopic analyses of wood dusts were made for the 500, 315, 200, and 100 μm fractions.

Determining the ignition temperature of airborne dusts

The experiments were conducted in a test equipment (VVUÚ, a.s., Ostrava, Czech Republic) that measures minimum ignition temperatures of airborne dusts (Fig. 1) with automatic weighing machines (Steinberg Systems, Łódź, Poland) and a HL 100 ZU EINHELL air compressor (Einhell Corp., Landau an der Isar, Germany), ALMEMO equipment (Ahlborn, Berlin, Germany). The procedure was conducted in line with EN 50281-2-1 (1999).



a) **b)**

Fig. 1. a) The test equipment establishing minimum ignition temperatures of airborne dusts: 1: electronic thermostat, 2: ceramic tube furnace, 3: mirror, 4: dust hopper, 5: thermocouple measuring the temperature inside the ceramic tube furnace, 6: Almemo, 7: manometer measuring the pressure inside the hopper, 8: compressed air tank, 9: air release valve, 10: steel frame, 11: air inlet tube, and 12: automatic weighing machine; b) Thermal imaging of ceramic heater using FLIR thermal imagining camera (FLIR Systems Inc., Antennvägen, Täby, Sweden).

First, the ceramic tube furnace was heated to 500 °C. Then, the wood dust sample (0.1 g and 0.2 g) was scattered inside the tube furnace with the air pressure of 10 kPa. The weight of the wood dust sample was determined on the basis of parameters from EN 50281-2-1 (1999) so that the whole sample of wood dust can be scattered all over the ceramic tube furnace. Higher quantities of wood dust were not effective, because the majority of the sample would remain in the hopper. The air pressures fed into the device were as follows: 10, 20, 30, and 40 kPa.

Once the flame was at its peak, the temperature of the ceramic tube furnace was slowly reduced in intervals of 20 °C, while maintaining the same parameters of the sample (the weight and the air pressure). The process was repeated until the wood dust ignited.

The minimum temperature at which the ignition of wood dusts did not occur was tested in 10 experiments with different volumes of wood dust and different air flow.

RESULTS AND DISCUSSION

Solid particles were characterized by the following parameters according to STN 26 0070 (1995): particle size and shape; cohesion (flowability of dust as loose material);

bulk density; moisture content; abrasiveness; gluing and hardening; production; and absorption of static electricity.

Padauk dust sample (Table 2) has a low average bulk density, so it is possible that the dust can be easily stirred up. Moisture content reaches standardized values as indicated by Jankowska and Kozakiewicz (2016).

Table 2. Bulk Density and Moisture Content of Dust Samples and the Sample Itself

African Padauk	Values	Visual
Average bulk density (kg/m^3)	167.3 ± 3.107	
Dust moisture (%)	5.34 ± 0.04	

Particle Sizes (Fractions) of Padauk Dust Samples

The percentages, starting from the 500 μm fraction (Fig. 2), are presented below. Bigger fractions occurred only minimally (at 1%). The same outcome was presented for the domestic tree species samples examined by Marková *et al*. 2016a,b; Očkajová *et al*. 2018). African padauk is a tropical tree with similar physical properties to tree species native to Slovakia. The dust particles of similar composition of spruce, oak, and beech wood (the most frequent tree species native to Slovakia) are formed during its processing.

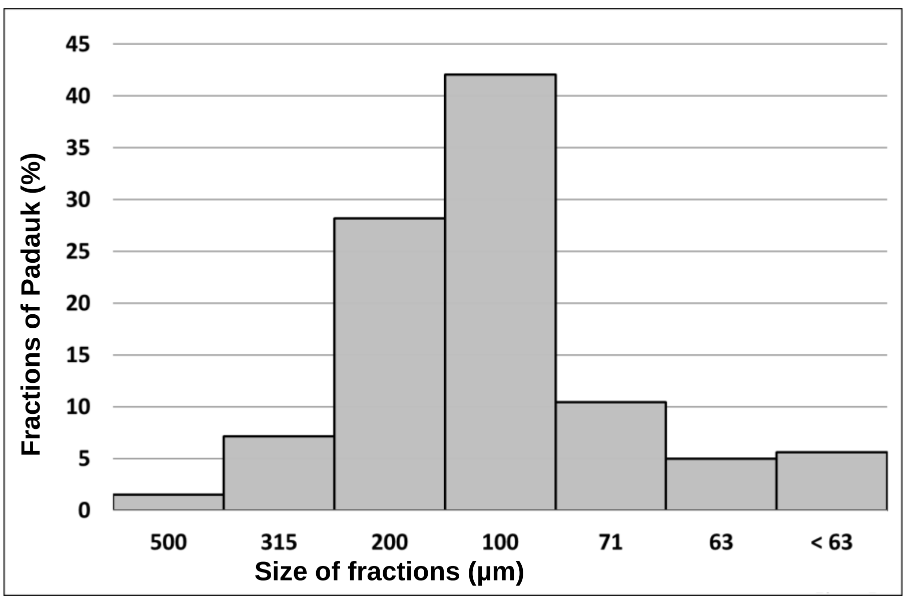


Fig. 2. Distributive granularity columns of padauk dust

Shape Analysis of Dust Particles

Schwarz *et al.* (2009) classified dusts according to their size as coarse (particle diameter of > 100 μm) and fine (particle diameter of < 100 μm). The value of 100 μm represents the boundary value of a particle size when it becomes airborne when the system is whirled (Schwarz *et al*. 2009; Kuracina *et al*. 2017; Dado *et al.* 2018; Chladil *et al.* 2019).

Padauk dust samples preserved their anatomical structure. The size analysis of the particles was performed for the fractions of 500, 315, 200, and 100 μm (Fig. 4). When zoomed in, they appeared different and had their own specific shapes.

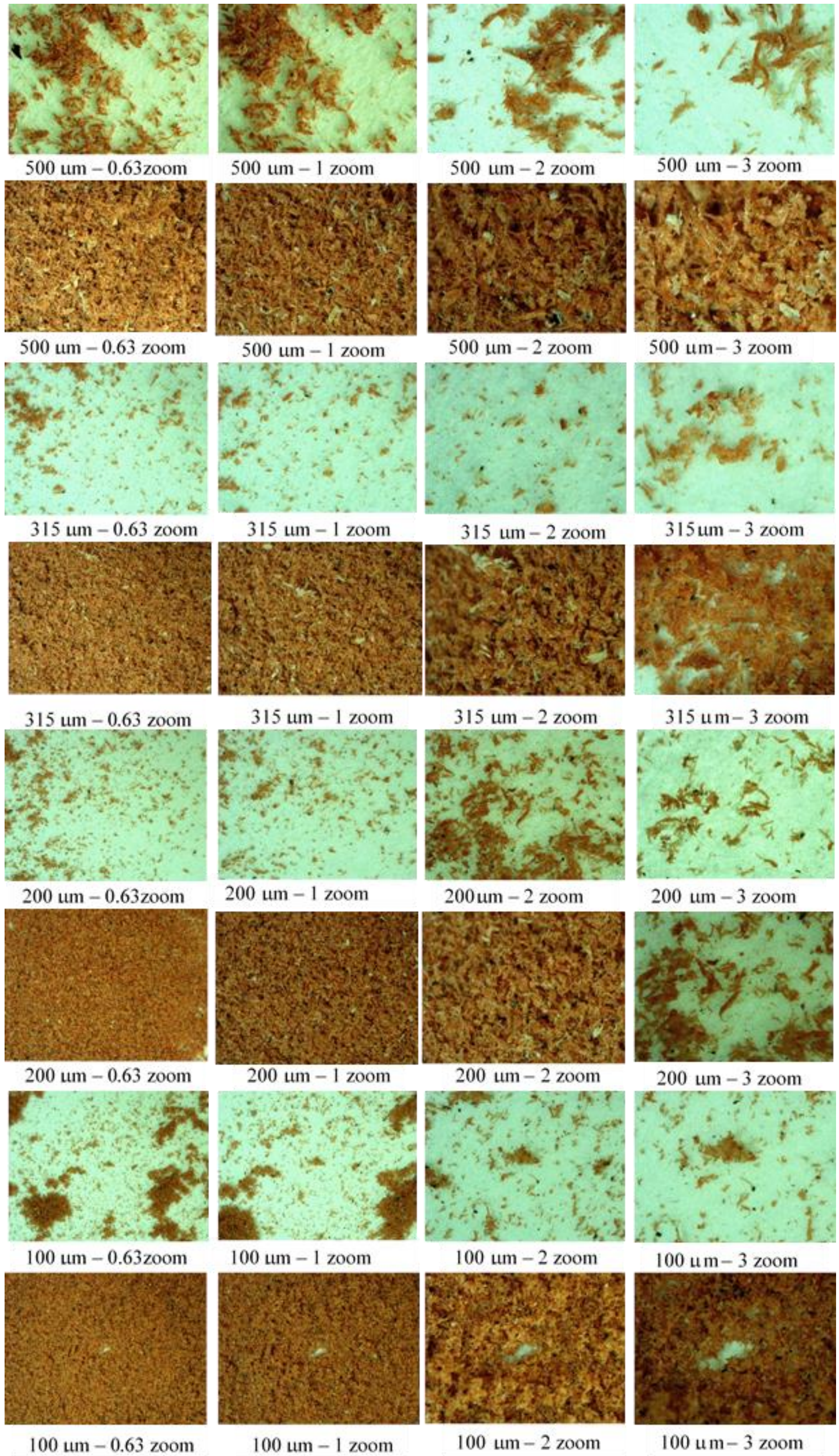


Fig. 3. Dust particles and their shape measured by Nikon Eclipse Ni with Nikon DS-Fi2 camera

Microscopic Dust Analysis

The particles of African padauk (Fig. 4) have the size of < 100 µm. The scans showed the fibers of the dust particles maintaining their anatomical structure (Alfonso *et al.* 1989; Wang *et al.* 2018).

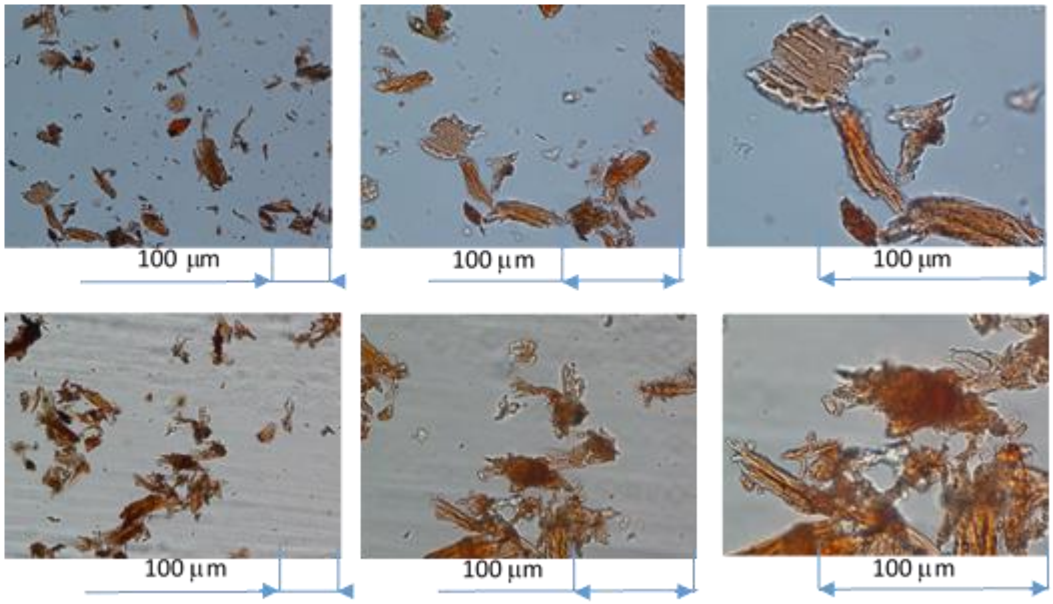


Fig. 4. Light microscopy images of padauk dust fibers with 100×, 200×, and 400× zoom

Ignition Temperature of Airborne Dust

The authors can conclude that the ignition of airborne wood dusts has a specific course of action. The ignition process of the sample had the following stages (Fig. 5):

1. An explosion initiated in the ceramic tube furnace after scattering the dust.
2. The unburned wood dust slid down and the products of combustion formed.
3. The wood dust ignited with the most intense flame.
4. The flame slowly faded and it was accompanied by moderate sparkling.
5. The dust in the ceramic tube furnace burned away.

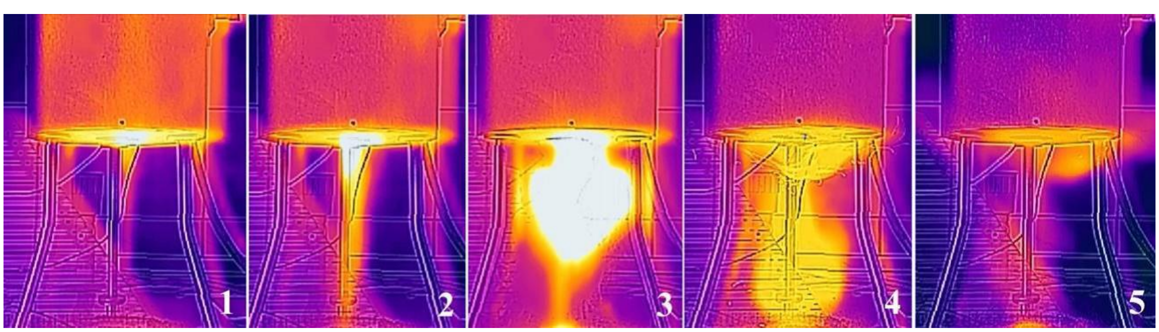
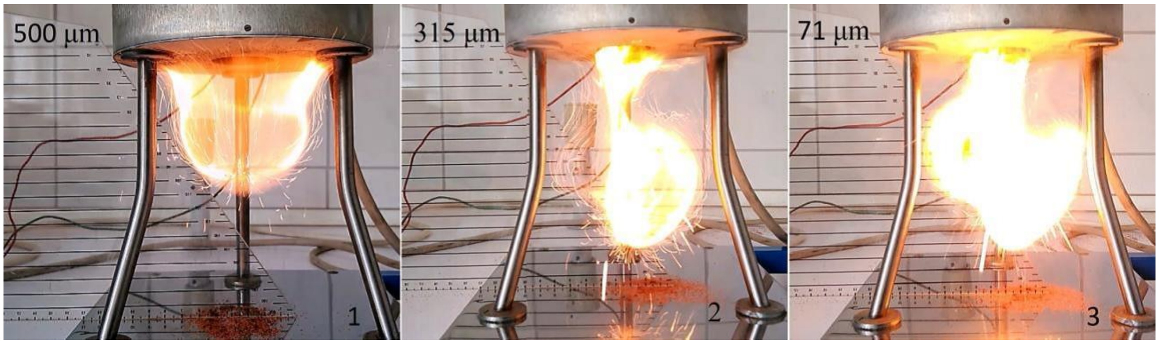


Fig. 5. Light microscopy images of padauk dust fibers with 10×, 100×, 200×, and 400× zoom *via* FLIR thermal imagining camera (FLIR Systems Inc., Antennvägen, Täby, Sweden)

The presentation of the maximum flame was made for the 500, 315, and 71 µm fractions (Fig. 6). The flame intensity changed: smaller particles resulted in a more intense flame. The flame of lower intensity was observed during the wood dust explosion of larger particles (the verification was possible by looking at the ruler placed behind the device).



a) b) c)

Fig. 6. The flame on ignition (conditions: 0.2 g of dust, air pressure of 30 kPa, temperature of the ceramic tube furnace 500 °C). Images were prepared using a Basler a602fc-2 high-speed camera (Basler AG, Ahrensburg, Germany). Legend: a) point of ignition for fraction 500 μm of padauk dust, b) point of ignition for fraction 315 μm of padauk dust, c) point of ignition for fraction 71 μm of padauk dust

The results determining the ignition temperature of airborne dust (Table 3) showed a decrease in values depending on the smaller fraction size. The results of the thermogravimetric analysis (Misse *et al*. 2018) showed initial temperature changes in the padauk sample at temperatures above 350 °C.

Table 3. Determination of Ignition Temperature (Flash Point) Fractions of the Wood Dust Padauk

Fractions (μm)	500	315	200	100	71	63	< 63
Ignition Temperature (°C)	390	390	390	380	370	370	370

The explosion of airborne wood dust and its risk assessment on the basis of ignition temperature was generally applied and accepted. However, it is necessary to take into account other factors that may have a considerable effect on ignition temperature (Mračková and Mialnko 2016).

Martinka *et al.* (2014) assessed the effect of particle size of Norway spruce (*Picea abies* L.) prepared using a belt sander on the minimum ignition temperature of airborne dust. They predicted an integral effect of particle size of wood dust on the combustion mechanism of airborne dust. Martinka *et al*. (2014) worked on the theory of Eckhoff (2003). Rockwell and Rangwala (2013) recognized two types of combustion mechanisms for airborne dust: Nusselt's mechanism and the flame mechanism. Nusselt's mechanism consists of heterogeneous combustion on the surface of dust particles. The flame mechanism lies in the disintegration of dust particles forming flammable gaseous products followed by flame burning (Bardon and Flatcher 1983; Martinka *et al*. 2014). In the process of wood dust burning, both mechanisms are applied, but flame mechanism seemed to prevail (Martinka *et al*. 2014). According to Mittal and Guha (1996) the minimum ignition temperature of airborne dust increased linearly as the particle size became increased.

CONCLUSIONS

1. Sieve analysis showed the percentages of the given fractions. The most common particle size was the 100 μm fraction ((42.14 ± 1.049%). The percentage of particles (< 100 μm) was 63.84%.
2. The shape of the particles and its wood morphology were preserved. Microscopy analysis confirmed that the anatomical structure of the wood dust particles remained unchanged as well.
3. The ignition temperature of the airborne dust was determined under experimental conditions, started at 390 °C (fraction 500 μm) and as the particles changed their size, it was reduced to 370 °C (fraction 71 μm).
4. As the particle size decreases, the risk of explosion increases (ignition temperature decreases).
5. The processing of tropical wood by sanding on a disc sander produces individual fractions of wood dust posing a risk of the formation of an explosive dust-air assembly. Therefore, precautions must be taken to prevent initiation sources from at least 370°C.

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