Wood Coating Dust Emission in the Malaysian Furniture Industry: A Case Study

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The objectives of this study were to evaluate the current dust extraction efficiency used in the Malaysian furniture industry and also the effectiveness of using engineered nanoparticle (ENP)-added coatings to reduce dust emission in the wood finishing operation. This study was in response to the enforcement of the Clean Air Regulation (2014), which requires significant improvements in the air quality and the work environment in the wood-based industry in Malaysia. A series of sanding experiments with different abrasive grit sizes and different coating types were conducted to determine the dust emission levels. The results suggested that higher capture velocity of 30 m/s was necessary to effectively capture the wood coating dust emitted. Further, ENP-added wood coatings did not differ markedly from conventional coatings with regard to dust emission characteristics. The study also revealed that total dust concentration had an inverse relationship, while the amount of finer dust particles was linearly related to the coating film hardness. Therefore, to comply with the Clean Air Regulation, the Malaysian furniture industry needs to significantly improve its dust extraction system.

Keywords: Wood coatings; Dust extraction; Clean air; Engineered nanoparticles; Energy; Sanding

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INTRODUCTION

The Malaysian furniture industry has developed substantially since its beginning as a cottage-based industry in the early 1980s. From an artisan-based industry, the furniture industry has emerged to become the fastest growing wood-based subsector within the domestic wood industry, and since the last few years, it contributes 40% to the annual total wood products export revenue (MTIB 2019). In 2019, total furniture exports reached 2.4 billion USD and provided employment to approximately 103,000 workers.

The Malaysian furniture industry growth trajectory has been well researched (Ratnasingam 2019), and it has been conclusively shown that industrial growth is driven primarily by incremental factor inputs (*i.e.*, raw material, labor, and capital), rather than productivity increments. Approximately 80% of all capital investments that went into furniture manufacturing focused on adding basic capacity without much emphasis on automation and state-of-the-art technology (Ratnasingam 2019). Hence, the labor-intensive nature of the furniture manufacturing industry has remained constant, as the application of automation and technology to reduce the use of low-cost labor was not a priority of the industry (MTIB 2019).

Furniture Manufacturing Work Environment

As reported by Ratnasingam *et al.* (2019), the low investment in automation and technology in the furniture manufacturing industry in Malaysia has perpetuated an unhealthy work environment, which is considered "3D" (*i.e.*, dirty, dangerous, and difficult). Such an environment is not attractive to the domestic workforce in the market, and as a result, furniture manufacturers face problems attracting local workers to replace the huge number of foreign contract workers presently employed in the industry. In fact, the government has begun to gradually reduce the number of foreign contract workers allowed in the furniture industry (MTIB 2019).

The dirty environment prevailing in the furniture manufacturing industry is attributed to the high waste, dust, and particulate emission levels within the industry. In fact, Koponen *et al.* (2011) reported that wood dust, particulate, and chemical emission in the furniture industry are higher than the mean exposure limit (MEL) of the prevailing health and safety standard. Further, several reports on the health and safety risks faced by workers in such environments have been well documented (Donaldson *et al.* 2000; Ratnasingam *et al.* 2010, 2012), and recommendations have been made to minimize the risks workers are exposed to.

Studies on the work environment in the furniture industry have shown repeatedly that the work station that poses the highest threat to workers' health and safety is the wood finishing or wood coating section (Osman and Pala 2009; Ratnasingam *et al.* 2010; Thetkauthuek *et al.* 2016; Wiggans *et al.* 2016). This work station has high emission levels of wood dust from white-wood sanding operations, particulate dust from the sanding of sealer or undercoat coatings, and the volatile organic compound (VOC) emissions from the coating mixture used (Ratnasingam *et al.* 2010, 2012). According to the National Institute of Occupational Safety and Health (NIOSH) in Malaysia, the workers' health and safety in the woodworking industry is often compromised, and cases of prolonged exposure have resulted in severe medical problems, which can be life threatening. It has been reported that financial losses due to sub-standard occupational safety and health compliance in the furniture industry in the country are approximately USD 5 million in productive work time, medical treatment, and compensation claims over the last decade. (NIOSH 2018).

To minimize the workers' risk of exposure to harmful dusts and chemicals, furniture manufacturers could adopt several mitigating measures, which include applying improved processing techniques, boosting the overall exhaust system, and using high quality wood finishes and coating materials. However, many furniture manufacturers believe that using the more expensive wood coatings, especially those with added engineered nanoparticles (ENP), would improve the wood coating's performance and its overall environmental compliance (Ratnasingam 2019). However, such a perception remains unanswered due to the lack of research data. Further, using ENP added wood coatings often incurs higher cost, which the furniture manufacturing industry may not be prepared to bear, as it operates on cost-competitiveness and strives to keep cost and investment as low as possible (Ratnasingam *et al.* 2019).

Engineered nanoparticles (ENPs), also called particulate nanomaterials, are engineered entities smaller than 100 nm along at least one physical axis (Koponen *et al.* 2009). Paint and lacquer manufacturers are among the largest users of ENP to achieve specific paint properties, such as water repellence, scratch resistance, improved durability, and antibacterial properties (Koponen *et al.* 2011). However, the physicochemical properties of the ENPs, their exposure characteristics, and the cost of such coatings, determine their long-term commercial success (Baron and Willeke 2001; Koponen *et al.* 2011). Though numerous studies are available on the potential health risks of nanomaterials (Oberdorster *et al.* 2007; Wiggans *et al.* 2016), studies on the sanding dust characteristics of ENP added wood coatings are limited (Koponen *et al.* 2011; Ratnasingam 2019).

However, the effectiveness of wood coatings with added ENP in reducing dust emission in the furniture and wood-based industry in Malaysia has not been studied, and remains a question posed by the furniture manufacturers.

Due to the lack of voluntary compliance measures to improve the working environment in furniture factories in accordance to the prevailing Factories and Machinery Act (DOSH 1967), it became necessary to enforce a legislation with more punitive actions to force furniture manufacturers to improve the work environment in their factories and improve the pollution index of the industry. In this context, the Malaysian government enacted the Environmental Quality (Clean Air) Regulation (2014) in late 2019, which required furniture manufacturers to improve the working environment in their factories. This regulation requires all furniture manufacturers to comply with the stipulated dust and VOC emission levels in both factory environments and boiler operation (DOE 2019). This regulation has serious ramifications for the furniture industry, as non-compliant factories operating beyond the stipulated grace-period can be penalized with hefty fines, or even forced to cease operation. In lieu of this development, this study was commissioned by the Malaysian Furniture Council (MFC) and the Muar Furniture Association (MFA) to provide insights and recommend economically viable solutions to furniture manufactures to ensure compliance with the regulation. Further, the sanding dust emission characteristics of common wood coatings used in the furniture industry was also a growing concern and warrant attention. Such studies are important, as they have far reaching implications for the development of standards and mitigating measures to overcome challenges faced by furniture manufacturers in the country (NIOSH 2018; Ratnasingam 2019). In fact, this study has also received the support of the National Institute of Occupational Safety and Health (NIOSH) of the country and is regarded as unique in this topic.

Therefore, the first objective of this study was to determine the optimum dust extraction air speed to achieve the targeted dust exposure level in the wood finishing workstation. A second objective of this study was to characterize the dust emission levels of nano-particle-added wood coatings relative to conventional wood coatings used in the furniture in Malaysia.

EXPERIMENTAL

The study was conducted in two parts. Part 1 aimed to establish the optimum air velocity for dust extraction in the typical furniture factory. Part 2 focused on determining the dust characteristics of different types of nanoparticle-added wood coatings relative to the conventional wood coatings. To ensure reliability and compliance with experimental protocols, the experimental techniques used in this study were discussed thoroughly with the National Institute of Occupational Safety and Health (NIOSH) of Malaysia. This was done to ensure that the results obtained were representative of industrial norms and could be adopted by NIOSH in their future dust emission guidelines and standards.

Details of dust exhaustion systems currently used in the furniture industry in Malaysia were reviewed and surveyed, with the assistance of the Technical Committee of the Malaysian Furniture Council (MFC). This enabled the prevailing working range of dust extraction parameters used in the factories to be established. Further, information on the overall energy consumption trend in the various furniture manufacturing processes was also collected, as it had implications on the overall manufacturing cost. In dust extraction systems, the capture velocity of the air at the hood's entrance plays the most important role (Ratnasingam *et al.* 2004), and the capture velocity currently used in furniture factories ranged from 15 m/s to 20 m/s. Capture velocity is defined as the velocity outside an exhaust necessary to capture the contaminant farthest away from the opening when it has released its initial energy, and to transport it into the opening of the hood (Ratnasingam *et al.* 2004).

In this study, the sanding operation in furniture manufacturing was simulated using a 3M pneumatically-operated orbital sander (Minnesota Mining & Manufacturing Company (3M), St. Paul, MN, USA) with an orbit diameter of 80 mm rotating at 10,000 rpm. Paper-backed aluminum oxide abrasive of the three most common grit sizes (150, 180, and 240) used for white-wood sanding operations in the furniture industry were used in this study. The sandpaper was attached to the orbital sander using the Velcro hook and loop system. The orbital sander was fixed to its position by a specially designed bracket, and the specimen was attached to a reciprocating platform moving at 15 mm·s^{-1}. The sanding pressure was kept constant by applying a constant force equivalent to 5 kg onto the orbital sander. This experimental configuration was adopted from the previous study by Ratnasingam *et al.* (2011, 2019). The experimental specimens of 25 mm × 200 mm × 500 mm in dimension were kiln-dried, machine-planed rubberwood (*Hevea brasiliensis*) with an average moisture content of 10 ± 2%. They were obtained from Sim Lee Sawmill in Maran, Malaysia.

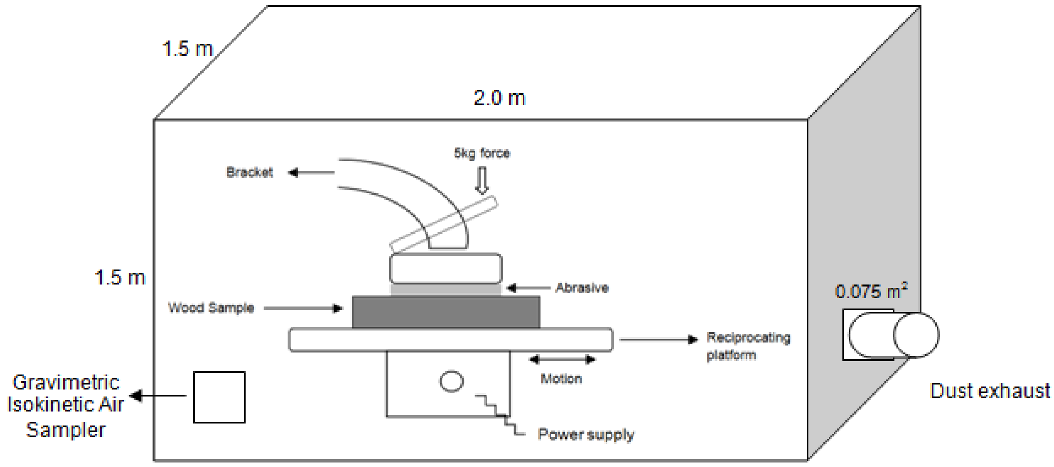

Fig. 1. Configuration of the abrasive sanding experimentation.

The sanding processes of the specimens were repeated in a concealed experimental chamber of 1.5 m × 2.0 m × 1.5 m that was fitted with a portable dust exhaust system (WESTAIR Air Filtration Model D14; Bibra Lake, Perth, Australia) with a 0.075 m^2 hood opening (Fig. 1). The hood opening, which resembled the industrial hood design commonly used, was 25 cm from the orbital sander. The exhaust air capture velocity was varied from 15 m/s to 30 m/s *via* a variable speed fan. A watt-meter was attached to the fan's motor to monitor power consumption during the experimental period. The residual dust concentration in the chamber of 4.5 m^3 in volume was measured using a calibrated gravimetric isokinetic air sampler (KANOMAX Instruments, Model 3905, Andover, NJ, USA) after a 30 min experimental period, at which point stable conditions had been achieved. An aerodynamic particle sizer (TSI Incorporated, Model APS-3300, Shoreview, MN, USA) with filters ranging from 100 μm to 5 μm was used to establish the dust particle size distribution during the experiments.

In the second part of the study, the three different undercoats or sealers, *i.e.*, nitro-cellulose (NC), alkyd-based (AC), and polyurethane-based (PU) lacquers, that were applied on the rubberwood specimens were provided by the Malaysian Paint Manufacturers Association (MyPMA, Selangor, Malaysia). The three sealers used had two variants. One type was the nanoparticle-added (TiO_2 and ZnO) sealer and the other was the conventional sealer. The wood sealers were applied onto the specimens using a roller-coater, and they were then dried in a drying oven to achieve an average dry-film thickness of 250 μm. The supplier and characteristics of the conventional and ENPs added sealers used remained anonymous to ensure impartiality of the experimentation. Ten specimens were used for each variant of the coating types in the study. Prior to the sanding process, the hardness of the sealer films was tested according to ASTM D3363-05 (2011) standard, where 3B is the softest and 9H is the hardest.

The coated specimens were then sanded using a similar sanding configuration as in Part 1 of this study. A 3M orbital sander attached with a 240-grit aluminum oxide sandpaper was used in the sanding operation. The sanding experiments were conducted in an experimental dust tunnel to ensure a moving air stream, and the capture air velocity was maintained at 20 m/s to reflect actual industrial conditions. Three gravimetric isokinetic air samplers (KANOMAX Instruments, Model 3905, Andover, NJ, USA) were placed 1.5 m apart along the length of the air tunnel to determine the average dust concentration during the sanding process. The size distribution of the sanding dust particles was measured using an aerodynamic particle sizer (TSI Incorporated, Model APS-3300, Shoreview, MN, USA), which had a series of filters ranging from 100 μm to 5 μm. This also enabled the proportion of air-borne dust (particles > 70 μm in size) and respirable dust (particles < 10 μm in size) emitted during the sanding process to be determined (NIOSH 2018).

The average stock removal rates of the specimens were ascertained by weighing the specimens before and after 30 min of sanding. The average roughness values (R_a) of the sanded surfaces were evaluated using a portable roughness recorder (MITUTOYO Surf-Test Model SJ-301, Kanagawa, Japan) over a length of 50 mm.

In order to evaluate the effect of the sanding operation on the gloss of the surface coating, the gloss of the coated surface after sanding with the three different abrasive sanding grit sizes were also evaluated. Gloss is a measure of the capacity of the surface to reflect more light in one direction than another. The gloss test is a comparative test in which samples are tested for their 60° gloss values and compared to the gloss value of the coating when it is applied to a black glass block, as in the ASTM D523-89 (1994) standard. A Schidmt F30 Parallel-Beam glossmeter (Pennsylvania, USA) was used for this purpose.

All experimental parameters (*i.e.* energy consumption, total dust concentration level, dust particle sizes and gloss level) from this study were subjected to statistical tests using SPSS version 10.1 statistical analysis software (IBM, Armonk, NY, USA). The significant differences between the mean values of the different test parameters for each test were evaluated using the Duncan's multiple range test and the analysis of variance (ANOVA) test. The significance level for these statistical tests was set at $P < 0.05$.

RESULTS AND DISCUSSION

Part I: Efficiency of Dust Exhausting System

From the survey of energy consumption trend in the furniture manufacturing industry in Malaysia, it was obvious that a significant amount of the energy consumed during the furniture manufacturing processes goes into dust extraction. As depicted in Fig. 2, dust extraction accounted for 75% of the average energy consumed in the various furniture manufacturing processes, with the abrasive sanding and wood coating sections registering higher energy consumption than the other operations. In fact, the energy demand for wood coating is significantly higher not only because of the higher total dust and particulate concentration, but also due to the need to ensure a higher pressure in the finishing-room to keep the air-borne dust particles away from this section (Gomez *et al.* 2014; de Paula *et al.* 2020).

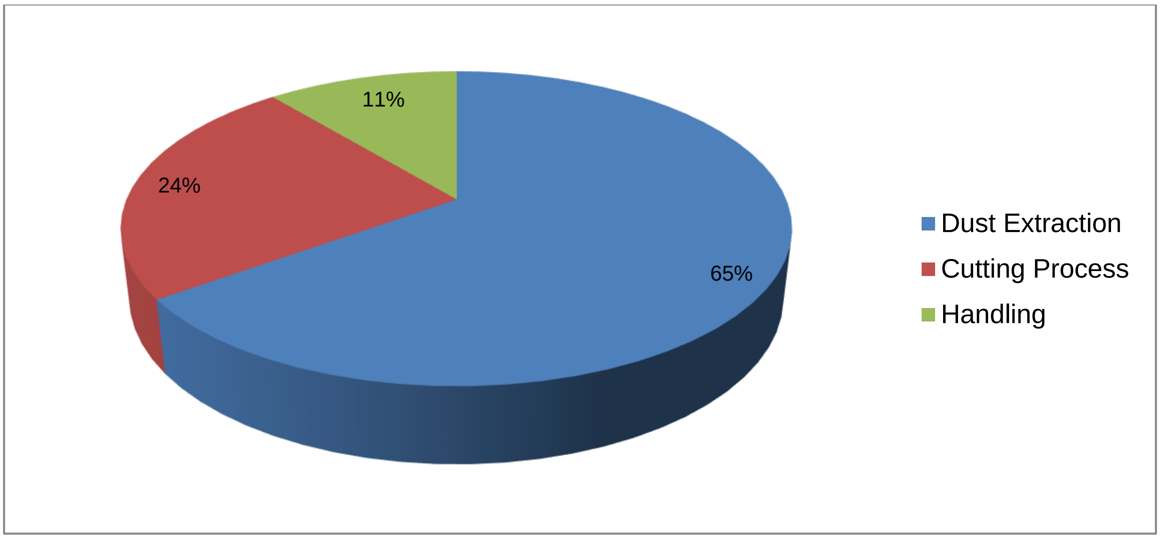

Fig. 2. Proportion of Power Consumption during Furniture Manufacturing Process

Typically, the total dust concentration level during the sanding operation is predetermined by the stock removal rate (Csanády and Magoss 2013). On the other hand, the dust particle size emitted during the sanding process is affected by the abrasive grit used, *i.e.*, lower sanding grits produce coarser dust particles and *vice versa*. When all other variables (such as sanding pressure and feed rate) are kept constant, lower sanding grits result in higher stock removal due to the larger grit particles, which penetrate deeper into the workpiece (Ratnasingam *et al.* 2004).

Figure 3 shows the sanding characteristics of the three different abrasive sanding grits used in the study. The total dust concentration emitted during the sanding process increased in the order of 150 > 180 > 240 sanding grit size, and the opposite was true for finer dust particle sizes (Welling *et al.* 2009).

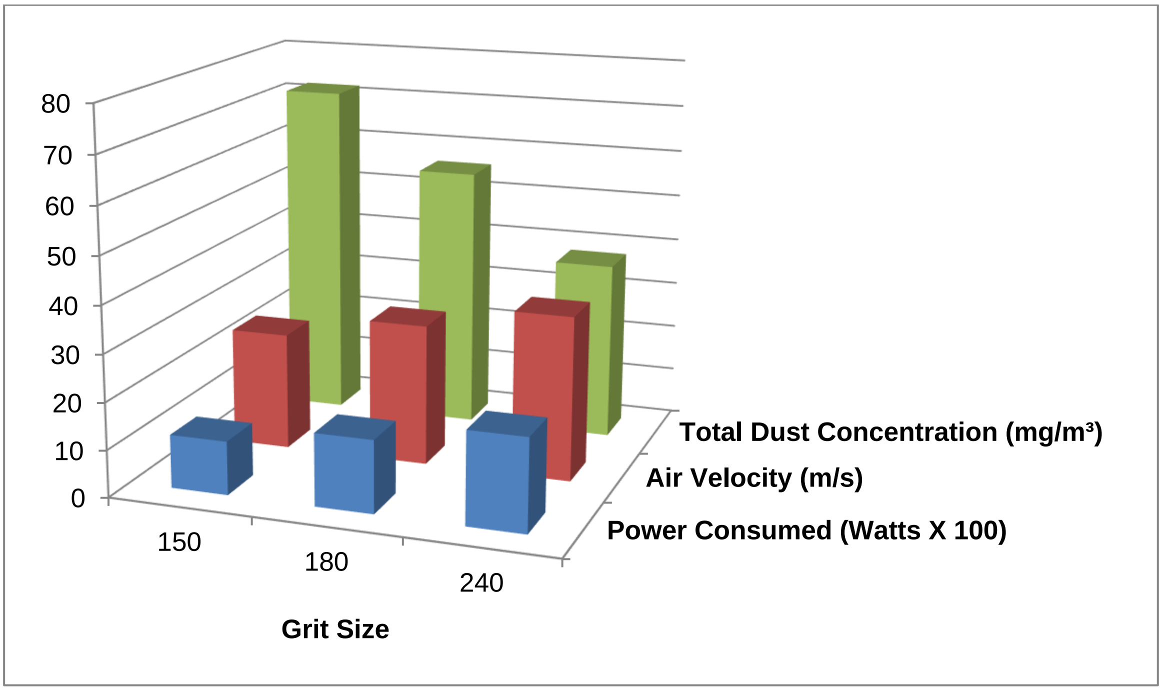

Fig. 3. Relationship between sanding operations and dust emission

The higher proportion of finer dust particles produced by the lower sanding grit required a higher capture air velocity to be effective in exhausting the air of the finer dust particles. This translated into higher energy requirements for dust exhaustion, which was in line with the findings of Ratnasingam *et al.* (2010, 2019). This finding reiterates the fact that dust exhaustion is an energy intensive operation. It was previously found that energy consumption during dust extraction accounted for approximately 77% of the total energy consumed during the abrasive sanding process (Ratnasingam *et al.* 2004). This finding was reinforced by a later report by Csánady and Magoss (2013) that energy consumption during the dust extraction constituted approximately 75% to 85% of the total energy consumption during the wood machining and sanding processes.

Against this background, the results from this study show that the capture air velocities of the dust extraction system currently used in furniture factories in Malaysia, which ranges from 15 m/s to 20 m/s, is insufficient to capture the sanding dust particles effectively. Therefore, it is apparent that higher capture air velocities of 30 m/s or higher, would be required to achieve the targeted permissible exposure limit (PEL) of 5 mg/m^3 of dust on an 8 h time-weighted average as stipulated in the dust emission requirement of the Factories and Machinery Act (DOSH 1967) of Malaysia.

In comparison, studies on dust emission in the few furniture factories in Singapore revealed significantly higher capture air velocities of between 30 m/s to up to 35 m/s in order to achieve the desired permissible exposure limit (PEL) of 5 mg/m^3 of dust (Ratnasingam 2019). Inevitably, it shows that from the dust extraction perspective, there appears to be compelling evidence to suggest that the presently installed dust extraction systems in the Malaysian furniture industry is below par and incapable of effectively improving the work environment. This also implies that compliance to the Clean Air Regulation (2014) would necessitate further improvements in the installed dust extraction system in furniture factories.

Part II: Dust Emission Characteristics of Wood Coatings

The results from this study indicated that the dust emission characteristics of nanoparticle-added wood coatings did not significantly differ compared to the conventional wood coatings (Fig. 4).

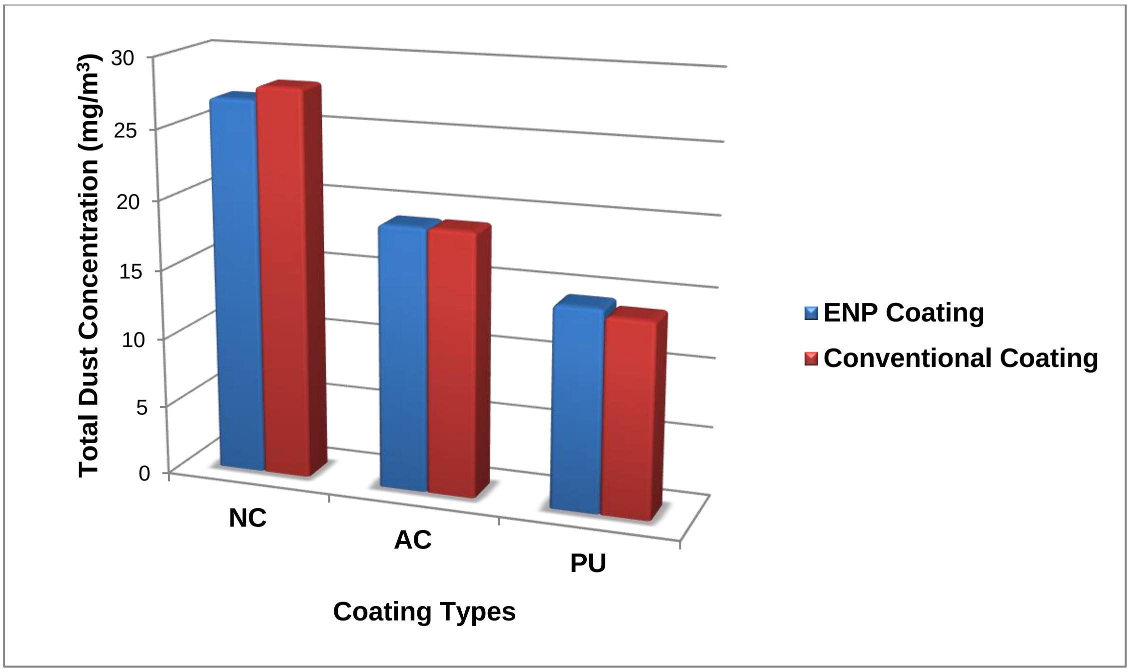

Fig. 4. Total dust concentration from the sanding of different sealer types

This finding was in line with those of previous studies (Koponen *et al.* 2011; Kaiser *et al.* 2013), which suggested that the addition of nanoparticles to the wood coating formulations improved its film properties and performance in service, rather than influencing its dust emission and environmental compliance.

Dust emission levels in the finishing workstation in furniture factories are known to exceed the permissible exposure limit (PEL) of 5 mg/m^3 on an 8 h time-weighted average, and the prevailing unhealthy exposure to dust has been well reported (Ratnasingam *et al.* 2012; NIOSH 2018). This study also revealed that the dust emission characteristics of wood coatings was influenced by the coating film hardness, which affects its ease of sanding and the resultant surface roughness. The resultant surface roughness of coated surfaces after sanding were reduced in the order of PU < AC < NC wood coatings, which was attributed to the differences in coating film hardness (Table 1). As the surface hardness of coating films increase, the scratching depth during the sanding operation decreases, which explains the lower surface roughness observed (Bulian and Graystone 2009). However, the power consumed during the sanding process was inversely proportional to the coating film hardness (Table 1), which was reported by Csánady and Magoss (2013) in their report on the mechanics of the sanding operation.

Table 1. Characteristics of Coated Wood Substrates

Coating	Specific Gravity	Film Hardness	Average Surface Roughness (R_a) in μm	Stock Removal Rate during Sanding (g/m^2)	Sanding Power Consumption (W/m^2)
Nitro Cellulose (NC)	0.29	3B	42	22	190
Alkyd-based (AC)	0.38	3H	34	17	240
Polyurethane-based (PU)	0.53	8H	26	12	330
Note: Film hardness test conducted according ASTM D3363-05 (2011) where 3B is the softest and 9H is the hardest					

The results of the study also showed that as the hardness of the coating film decreased, the total concentration of dust particles produced increased. Therefore, the amount of total dust particles released from the different wood coating films increased in the order of NC > AC > PU wood coatings. However, from the particle size distribution analysis, it was apparent that harder coating films produced significantly finer dust particles compared to the softer coating film (Fig. 5). The different stock removal rate and the different polymeric characteristics of the coatings could explain the variations observed in the sanding dust particles distribution. NC coatings, which are often straight polymers are usually produces softer coating films compared to the cross-linked AC and PU coatings. Further, the larger the molecular size of the resin, the harder is the resultant coating film (Vorbau *et al.* 2009). The proportion of coarser inhalable dust (< 100 μm) was greater than that of finer respirable dust (< 10 μm) emitted from the softer coating film compared to harder coating. Against this background, this finding warrants a review of current industrial air filtration practices of capturing dust above 50 μm in average particle diameter in the furniture industry in Malaysia, as it fails to capture small sized particulates which poses a higher health risks to workers (NIOSH 2018).

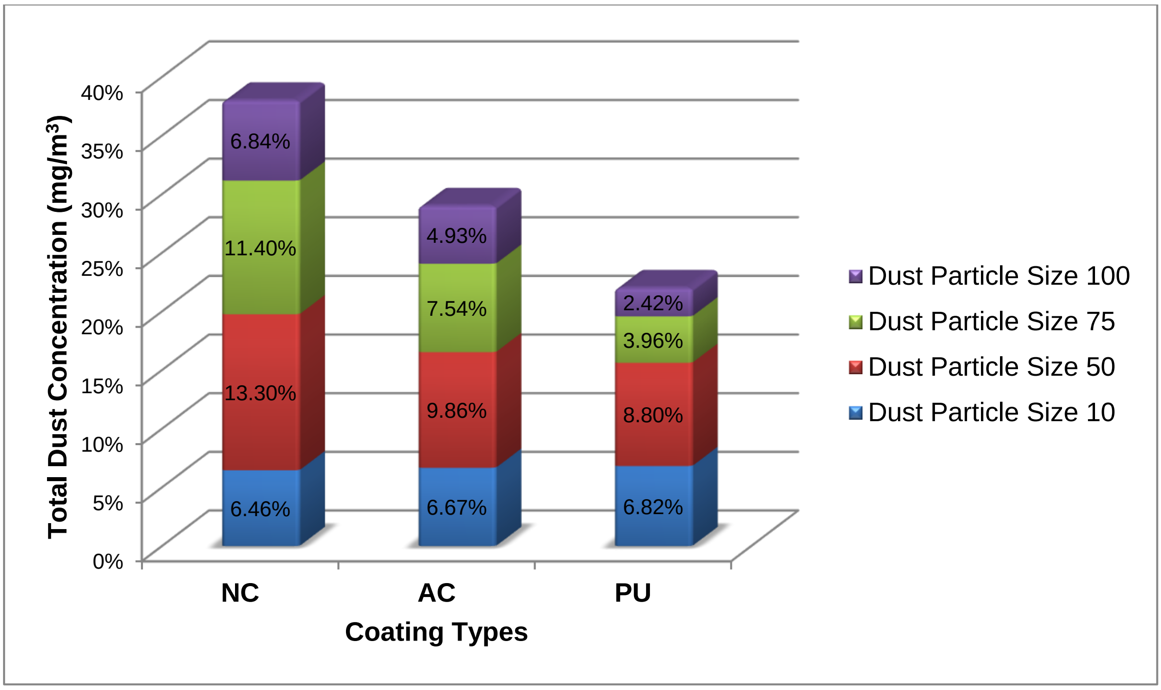

Fig. 5. Dust emission characteristics of common wood coatings

From a manufacturing perspective, it is evident that different abrasive sanding grits would lead to different gloss levels on coated surfaces (Salca *et al.* 2017; Slabejová and Šmidriaková 2018; Mikušová *et al.* 2019). In this study, it was also found that different wood coatings achieved different gloss levels when sanded with the different abrasive grit sizes. The results revealed that film hardness appeared to be the single most important feature of the coating film in determining the gloss level achieved, as harder coating film show higher resistance to gloss reduction, compared to a softer coating film (Fig. 6). Therefore, gloss reduction in this study was in the order of PU > AC > NC, suggesting that in determining the optimum abrasive grit size to be used in the sanding of coated surface, it is also important to take into consideration the desired gloss level.

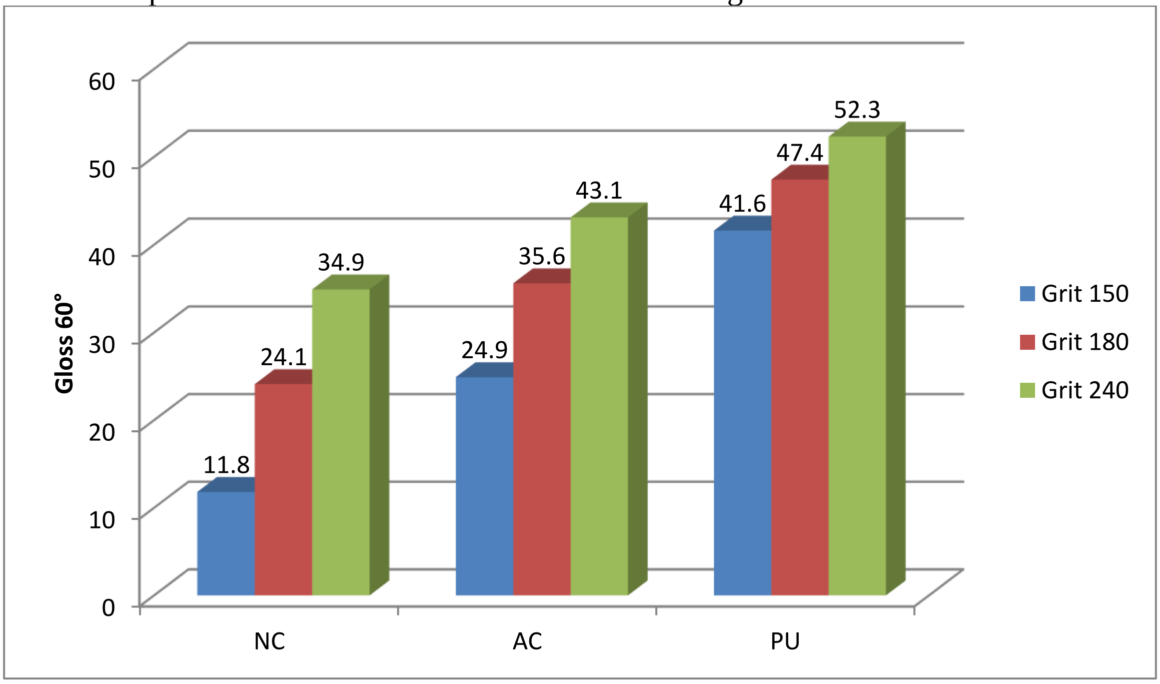

Fig. 6. Effect of Abrasive Grit Size on Gloss Level

INDUSTRIAL IMPLICATIONS

This study revealed an urgent need to re-examine the current single-point dust exposure standard that is applied to all woodworking environments in Malaysia, as the single standard is insufficient to mitigate the safety and health risks posed by the dust particles emitted from the different wood processing operations, especially those in the wood finishing or wood coating operations. The results also imply that ENPs added wood coatings do not necessarily lower dust emission and cannot be perceived to be an instant solution to reduce particulate emission in the wood coating operation in the furniture industry. Further, this study also implies the necessity to review the current dust extraction and filtration standard in use in the furniture manufacturing industry in the country and encourage the application of multiple-level filters to capture dust particles of different particle sizes. In this context, the results from this study will supplement the NIOSH (2018) report by highlighting the prevailing weaknesses in the current industrial practices and standards related to dust emission in the furniture industry. Further, it provides the necessary justification to review the existing dust emission and its control standards as stipulated in the Factories and Machinery Act (DOSH 1967). In addition, a higher standard may be necessary to ensure a better and cleaner work environment compliant with the requirements of the Clean Air Regulation (2014).

CONCLUSIONS

1. As the fineness of the dust particles increases, a higher capture air velocity of the dust extraction system is necessary in order to be effective.
2. Engineered nanoparticles (ENPs) added wood coatings did not have significantly different dust emission characteristics compared to the conventional wood coatings. In fact, the use of ENP-added wood coatings to reduce dust emission appears to be over-estimated.
3. As the hardness of the coating film increases, it tends to produce more finer dust particles and vice-versa.
4. There is an urgent need to review the existing single-point dust emission standard in the woodworking industry in Malaysia to ensure compliance with the Clean Air Regulation (2014).

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