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Study of Health Implications Effects in Laser Paint Removal Process Based on $PM_{1.0}$ and $PM_{10.0}$ Measurements

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Abstract

Health implications to the staff incharged was studied by measuring mass density (*N*) of two types of particulate matter ($PM_{1.0}$ and $PM_{10.0}$) concentration produced during laser paint removal process over three different types of car coated substrate samples A, B and C. The lowest $PM_{1.0}$ and $PM_{10.0}$ concentrations detected for those substrate samples during 10 minute laser irradiation were 0.693 mg/m^3 and 1.586 mg/m^3, which was far exceed compared to the recommendation suggested by World Health Organization (WHO). However, laser paint removal techniques was considered safe compared than chemical paint stripping technique if smooth air ventilation in workplace was properly set-up and inhalation to $PM_{1.0}$ and $PM_{10.0}$ was greatly prevented by using protective mask.

1. Introduction

Conventional chemical based stripping and grit blasting known as regular techniques practiced in Malaysian automotive industry for car repaint. However, neither of these techniques is ideal as both resulting in environmental imbalance due to the generation of a large amount of waste and the process is unfavorable due to high cost especially labor cost as shown in Figure 1 and Table 1, respectively (Arthur et al., 2008; Naguy & Straw, 2010; Walters et al., 1998; Wolf, 2009).

Recently, research studies shows that laser cleaning can be a good alternative candidate to replace conventional chemical cleaning in paint removal purposes which consume much water and cost, (Chen et al., 2010; Razab et al., 2014a; Razab et al., 2014b; Razab et al., 2014e; Steen & Mazumder, 2010). This new cleaning methods also has advantages in absence of mechanical damage of the metal surface and at the same time increase the effectiveness of paint removal, (Veiko et al., 2008). Laser paint removal involves few complex mechanisms such as photothermal, photochemical and mechanical effects, which the exact mechanisms depend on the laser parameters and the physical and chemical properties of the paint materials (Koh, 2006; Razab et al., 2014c; Razab, et al., 2014e). Unique characteristics of laser cleaning utilize the versatile, precise, controllable, selective and environmental friendly process to strip the paint from substrate surfaces in many industries, (Lee & Watkins, 2000).

Health effects and environment pollution in laser paint removal is considered minimal in term of producing toxic, air contaminants, particulate matter,

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various metal particles and hazardous waste compare to conventional chemical techniques. However, the severe implications to these conditions are still exist (Mongelli, 2005; Razab et al., 2014d; Wolf, 2009). To address this issue, the experimental study regarding health implications effects in laser paint removal process based on $PM_{1.0}$ and $PM_{10.0}$ concentration measurements was done at Medical Physics Laboratory, School of Physics, Universiti Sains Malaysia, Penang.

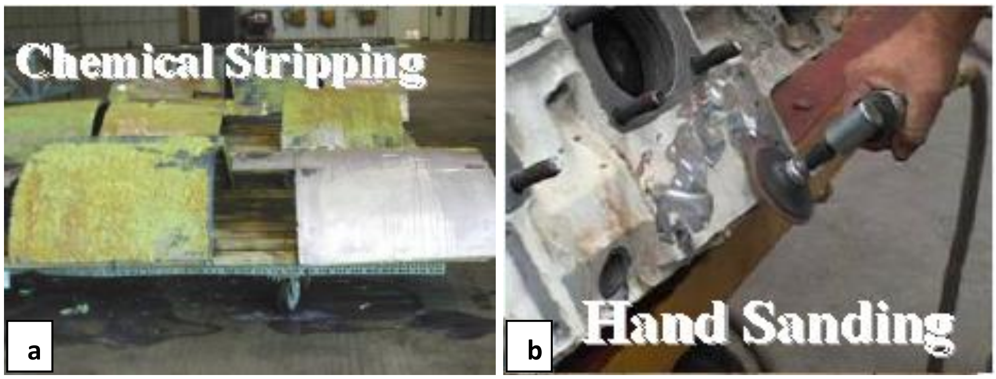

Figure 1: Conventional paint stripping technique is an expensive, time consuming process and tends to generate large amount of hazardous waste: a. Chemical stripping process b. Hand sanding process (Naguy & Straw, 2010).

Table 1: Cost comparison of currently used technology and laser stripping technique for four stripping applications where such a laser system could be used (Wolf, 2009).

Stripping application	Current stripping technique	Cost of stripping with current technology	Cost of stripping with laser technique
Aircraft	Chemical stripping	$36,325	$25,920
Storage tank	Sand blasting	$54,906 to $57,796	$24,729
Ground vehicles	Media blasting	$927,917	$509,389
Navy parts	Burn-off oven	$2,289	$2,891

2. Materials and methods

2.1 Substrate sample preparation for laser irradiation

In this study, substrate samples were obtained from right front door of three car models, A, B and C. These samples were acquired from car workshops and spare parts around Kota Bharu, Kelantan, Malaysia. The doors were cut in small rectangular pieces, approximately 4 x 4 cm^2 in size. Each substrate sample was labeled by unique number at the back of sample for identification, sort of number 1 for sample 1, number 2 for sample 2 and so on. There are 54 rectangular shapes of substrate samples prepared for this study, consisting of 18 samples for each three types of car models.

In addition, paint thickness for substrate samples of car models A, B and C were determined by using CEM DT-156 Paint Coating Thickness Gauge Tester F/NF Probe which ranged from 92 – 134 μm, 196 – 450 μm, 219 – 283 μm, respectively and never repaints.

For this study, ten spotted laser irradiation was done on each substrate sample with 10 J/cm^2 increments of laser fluence (*F*) by manipulating the pulse width (PW), repetition rate (RR) and beam size (BS) as listed in the Table 2 and Figure. 2.

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Table 2: Laser parameters considered for 3 mm and 5 mm BS with varies in *F*, PW and RR.

Sample number	Number of irradiation	BS (mm)	*F* (J/cm^2)	PW (ms)	RR (Hz)
1	10	3	210 - 300	100	1.0
2	10	3	210 - 300	200	1.0
3	10	3	210 - 300	300	1.0
4	10	3	210 - 300	100	1.5
5	10	3	210 - 300	200	1.5
6	10	3	210 - 300	300	1.5
7	10	3	210 - 300	100	2.0
8	10	3	210 - 300	200	2.0
9	10	3	210 - 300	300	2.0
10	10	5	150 - 240	100	1.0
11	10	5	150 - 240	200	1.0
12	10	5	150 - 240	300	1.0
13	10	5	150 - 240	100	1.5
14	10	5	150 - 240	200	1.5
15	10	5	150 - 240	300	1.5
16	10	5	60 - 150	100	2.0
17	10	5	60 - 150	200	2.0
18	10	5	60 - 150	300	2.0

*Note: Maximum *F* for 3 mm BS is 300 J/cm^2 for all laser parameters. Meanwhile the maximum *F* for 5 mm BS is 240 J/cm^2 set-up with RR 1.0 and 1.5 Hz whereas 150 J/cm^2 set-up with RR 2.0 Hz.

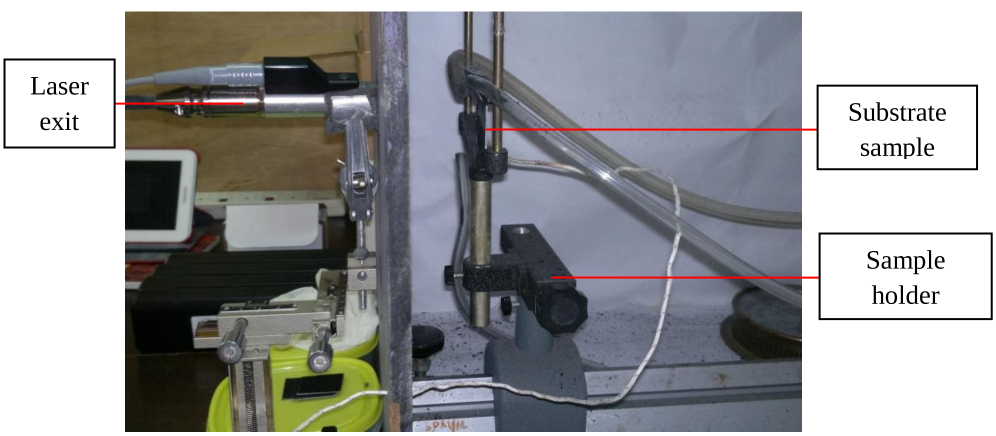

Figure 2: Experimental set-up for laser paint removal on the car coated substrate.

2.2 Particulate matter measurements

$PM_{1.0}$ and $PM_{10.0}$ were measured during laser paint removal process by using DustTrak Aerosol Monitor 8520. Both particulate matter (PM) measurements were based on 10 minutes counting started from first irradiation on each certain substrate samples as shown in Figure 2. Two DustTrak 8520 aerosol monitor was used together with the required inlet nozzle for specific size measurement of $PM_{1.0}$ and $PM_{10.0}$, respectively. $PM_{1.0}$ and $PM_{10.0}$ were measured in a close wood box with size 60.5 cm length, 40.5 cm wide and 40.5 cm height. The experimental set-up for $PM_{1.0}$ and $PM_{10.0}$ measurements was shown in Figure 3.

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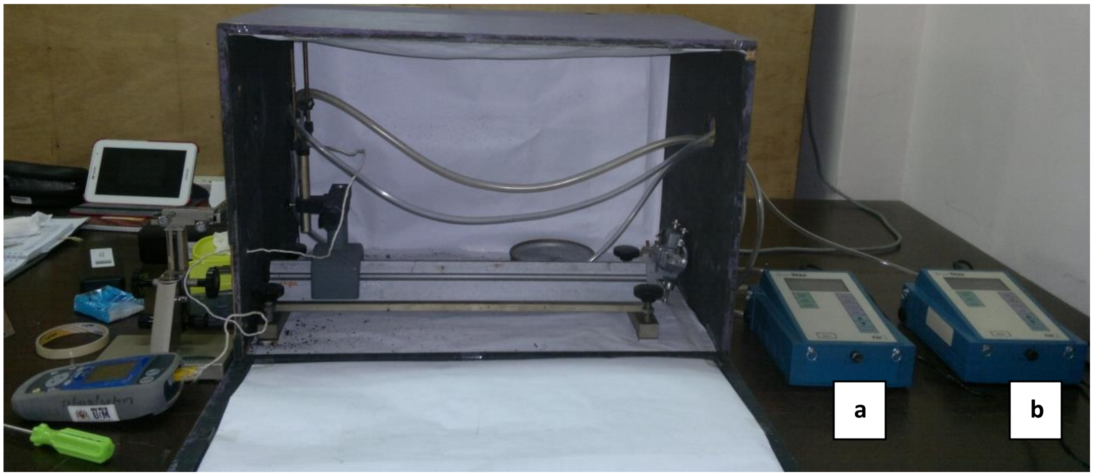

Figure 3: Experimental set-up of DustTrak 8520: a. DustTrak 8520 was set-up for $PM_{10.0}$ and ready for measurement b. DustTrak 8520 was set-up for $PM_{1.0}$ and ready for measurement.

3. Results and discussions

3.1 World Health Organization Guidelines

Previously there are no threshold concentration of particulate matter proposed due to unable to define a threshold below an adverse effects expected (Brunekreef & Holgate, 2002). However, World Health Organization (WHO) proposed the specific guideline for each pollutant of particulate matter based on current scientific findings and interim target values based on selected cities of the world in 2005 (Krzyzanowski & Cohen, 2008; WHO, 2006). Table 3 and 4 explained the annual and 24-hour mean concentrations of allowable PM for air quality guideline (AQG) (WHO, 2006). The recommended values for annual and 24-hour mean concentrations are 20 x 10^{-3} mg/m^3 and 50 x 10^{-3} mg/m^3 for $PM_{10.0}$ and 10 x 10^{-3} mg/m^3 and 25 x 10^{-3} mg/m^3 for $PM_{2.5}$ (Krzyzanowski & Cohen, 2008; WHO, 2006).

Table 3: WHO AQG and interim targets for annual mean concentrations recommended for long term exposures (WHO, 2006).

NIL	$PM_{10.0}$ (mg/m^3)	$PM_{2.5}$ (mg/m^3)	Basis for the selected level
Interim target 1 (IT-1)	70 x 10^{-3}	35 x 10^{-3}	These levels are associated with about a 15% higher long-term mortality risk relative to the AQG level.
Interim target 2 (IT-2)	50 x 10^{-3}	25 x 10^{-3}	In addition to other health benefits, these levels lower the risk of premature mortality by approximately 6% [2–11%] relative to the IT-1 level.
Interim target 3 (IT-3)	30 x 10^{-3}	15 x 10^{-3}	In addition to other health benefits, these levels reduce the mortality risk by approximately 6% [2-11%] relative to the IT-2 level.
Air quality guideline (AQG)	**20 x 10^{-3}**	**10 x 10^{-3}**	These are the lowest levels at which total, cardiopulmonary and lung cancer mortality have been shown to increase with more than 95% confidence in response to long-term exposure to PM2.5.

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Table 4: WHO AQG and interim targets for 24-hour mean concentrations recommended for short term exposures (WHO, 2006).

NIL	$PM_{10.0}$ (mg/m^3)	$PM_{2.5}$ (mg/m^3)	Basis for the selected level
Interim target 1 (IT-1)	150×10^{-3}	75×10^{-3}	Based on published risk coefficients from multi-centre studies and meta-analyses (about 5% increase of short-term mortality over the AQG value).
Interim target 2 (IT-2)	100×10^{-3}	50×10^{-3}	Based on published risk coefficients from multi-centre studies and meta-analyses (about 2.5% increase of short-term mortality over the AQG value).
Interim target 3 (IT-3)	75×10^{-3}	37.5×10^{-3}	Based on published risk coefficients from multi-centre studies and meta-analyses (about 1.2% increase in short-term mortality over the AQG value).
Air quality guideline (AQG)	**50×10^{-3}**	**25×10^{-3}**	Based on relationship between 24-hour and annual particulate matter levels.

3.2 Health risk in laser paint removal process

Concentration of $PM_{1.0}$ and $PM_{10.0}$ or aerosol by-products from laser paint removal process is depending on physical and chemical compositions of the ablated paint material and the laser parameters were used sort of *F*, PW, RR and BS (Dewalle et al., 2010; Kusch et al., 2003; Ostrowski et al., 2007).

By assuming the spatial distributions of energy is homogenous for each shot on the painted material, it is possible to normalize the measurements with respect to the interaction of surface area (Lee & Cheng, 2006; Razab, et al., 2014d). Thus, each measurement of particle mass is related to one laser shot and 1.0 cm^2 of ablated paint. Equation 1 depicts the averaging method which was used to acquire the mass density of particles, *N* (Dewalle, et al., 2010).

$$N = d_f \,.\, (C_{Av} - C_{noise}) \,.\, Q \,.\, \Delta_t \,/\, (n_{shots} \times A) \qquad (1)$$

Where *N* is the mass density of particulate matter per one laser shot and 1.0 cm^2 ($mg/shot/cm^2$), d_f is the dilution factor, C_{Av} (mg/m^3) is the average concentration issued from the measurement device during Δ_t, C_{noise} (mg/m^3) is the average concentration issued before laser shoots, *Q* (m^3/min) is the constant air flow rate of the device and was fixed at 0.0017 m^3/min, Δ_t (min) is the time interval for the particulate matter accounted and was fixed at 10 minutes, n_{shots} is the number of laser shoots within Δ_t and was fixed at 10 irradiations, *A* (cm^2) is the irradiated crater area which fixed at 0.071 cm^2 for beam size 3 mm whereas 0.196 cm^2 for beam size 5 mm, respectively. For this analysis, the dilution factor d_f is assumed to fix at value 1 due to no diluter was build in to the DustTrak 8520. The average of $PM_{1.0}$ and $PM_{10.0}$ determined by using DustTrak 8520 was applied in the Equation 1 to obtain the *N* for each substrate sample A, B and C as shown in Table 5.

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Table 5: Summarized of mass density (N) of $PM_{1.0}$ and $PM_{10.0}$ per one laser shot and 1.0 cm^2 for substrate sample A1 – A18, B1 – B18 and C1 – C18.

Sample	RR (Hz)	H (%)	d_f	Q (m^3/min)	n_{shots}	Δ_t (min)	A (cm^2)	C_{noise} (mg/m^3)	Types of PM	C_{av} (mg/m^3)	N ($mg/shot/cm^2$)
A1	1	73	1	0.0017	10	10	0.071	0.003	$PM_{1.0}$	0.693	0.0166
									$PM_{10.0}$	1.598	0.0384
A2	1	71	1	0.0017	10	10	0.071	0.005	$PM_{1.0}$	0.948	0.0227
									$PM_{10.0}$	2.052	0.0493
A3	1	71	1	0.0017	10	10	0.071	0.006	$PM_{1.0}$	1.81	0.0434
									$PM_{10.0}$	2.575	0.0619
A4	1.5	73	1	0.0017	10	10	0.071	0.004	$PM_{1.0}$	1.031	0.0247
									$PM_{10.0}$	2.291	0.0551
A5	1.5	71	1	0.0017	10	10	0.071	0.005	$PM_{1.0}$	1.067	0.0256
									$PM_{10.0}$	2.131	0.0512
A6	1.5	77	1	0.0017	10	10	0.071	0.001	$PM_{1.0}$	1.717	0.0413
									$PM_{10.0}$	2.856	0.0687
A7	2	74	1	0.0017	10	10	0.071	0.002	$PM_{1.0}$	1.388	0.0334
									$PM_{10.0}$	2.798	0.0673
A8	2	73	1	0.0017	10	10	0.071	0.003	$PM_{1.0}$	1.246	0.0299
									$PM_{10.0}$	2.182	0.0525
A9	2	74	1	0.0017	10	10	0.071	0.002	$PM_{1.0}$	2.018	0.0485
									$PM_{10.0}$	3.185	0.0766
A10	1	73	1	0.0017	10	10	0.196	0.004	$PM_{1.0}$	1.775	0.0153
									$PM_{10.0}$	2.505	0.0217
A11	1	72	1	0.0017	10	10	0.196	0.004	$PM_{1.0}$	1.775	0.0153
									$PM_{10.0}$	2.453	0.0212
A12	1	71	1	0.0017	10	10	0.196	0.002	$PM_{1.0}$	1.462	0.0126
									$PM_{10.0}$	2.794	0.0242
A13	1.5	72	1	0.0017	10	10	0.196	0.005	$PM_{1.0}$	2.098	0.0181
									$PM_{10.0}$	3.884	0.0336
A14	1.5	72	1	0.0017	10	10	0.196	0.004	$PM_{1.0}$	1.298	0.0112
									$PM_{10.0}$	2.545	0.0220
A15	1.5	76	1	0.0017	10	10	0.196	0.003	$PM_{1.0}$	1.731	0.0150
									$PM_{10.0}$	3.386	0.0293
A16	2	74	1	0.0017	10	10	0.196	0.003	$PM_{1.0}$	3.167	0.0274
									$PM_{10.0}$	3.516	0.0304
A17	2	72	1	0.0017	10	10	0.196	0.005	$PM_{1.0}$	2.65	0.0229
									$PM_{10.0}$	3.145	0.0272
A18	2	74	1	0.0017	10	10	0.196	0.005	$PM_{1.0}$	5.578	0.0483
									$PM_{10.0}$	5.446	0.0471
B1	1	73	1	0.0017	10	10	0.071	0.003	$PM_{1.0}$	2.453	0.0590

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									$PM_{10.0}$	3.878	0.0933
B2	1	77	1	0.0017	10	10	0.071	0.002	$PM_{1.0}$	1.328	0.0319
									$PM_{10.0}$	2.35	0.0565
B3	1	76	1	0.0017	10	10	0.071	0.003	$PM_{1.0}$	2.522	0.0607
									$PM_{10.0}$	5.364	0.1291
B4	1.5	72	1	0.0017	10	10	0.071	0.004	$PM_{1.0}$	3.217	0.0774
									$PM_{10.0}$	5.512	0.1326
B5	1.5	73	1	0.0017	10	10	0.071	0.003	$PM_{1.0}$	1.875	0.0451
									$PM_{10.0}$	4.472	0.1076
B6	1.5	76	1	0.0017	10	10	0.071	0.004	$PM_{1.0}$	3.701	0.0890
									$PM_{10.0}$	7.179	0.1728
B7	2	73	1	0.0017	10	10	0.071	0.002	$PM_{1.0}$	1.814	0.0436
									$PM_{10.0}$	4.848	0.1167
B8	2	72	1	0.0017	10	10	0.071	0.002	$PM_{1.0}$	1.318	0.0317
									$PM_{10.0}$	3.36	0.0809
B9	2	76	1	0.0017	10	10	0.071	0.003	$PM_{1.0}$	2.204	0.0530
									$PM_{10.0}$	6.268	0.1509
B10	1	73	1	0.0017	10	10	0.196	0.005	$PM_{1.0}$	4.081	0.0353
									$PM_{10.0}$	6.839	0.0592
B11	1	76	1	0.0017	10	10	0.196	0.003	$PM_{1.0}$	5.08	0.0440
									$PM_{10.0}$	8.276	0.0716
B12	1	75	1	0.0017	10	10	0.196	0.002	$PM_{1.0}$	5.517	0.0478
									$PM_{10.0}$	12.48	0.1081
B13	1.5	72	1	0.0017	10	10	0.196	0.005	$PM_{1.0}$	4.671	0.0404
									$PM_{10.0}$	7.591	0.0657
B14	1.5	71	1	0.0017	10	10	0.196	0.006	$PM_{1.0}$	3.774	0.0326
									$PM_{10.0}$	7.686	0.0665
B15	1.5	76	1	0.0017	10	10	0.196	0.003	$PM_{1.0}$	5.065	0.0438
									$PM_{10.0}$	14.49	0.1255
B16	2	73	1	0.0017	10	10	0.196	0.003	$PM_{1.0}$	1.87	0.0162
									$PM_{10.0}$	4.161	0.0360
B17	2	72	1	0.0017	10	10	0.196	0.004	$PM_{1.0}$	2.207	0.0191
									$PM_{10.0}$	4.349	0.0376
B18	2	70	1	0.0017	10	10	0.196	0.006	$PM_{1.0}$	4.664	0.0403
									$PM_{10.0}$	7.898	0.0683
C1	1	70	1	0.0017	10	10	0.071	0.007	$PM_{1.0}$	0.699	0.0167
									$PM_{10.0}$	1.592	0.0382
C2	1	71	1	0.0017	10	10	0.071	0.008	$PM_{1.0}$	0.987	0.0236
									$PM_{10.0}$	1.586	0.0380
C3	1	77	1	0.0017	10	10	0.071	0.004	$PM_{1.0}$	1.086	0.0261

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									$PM_{10.0}$	2.173	0.0522
C4	1.5	78	1	0.0017	10	10	0.071	0.003	$PM_{1.0}$	0.933	0.0224
									$PM_{10.0}$	1.775	0.0427
C5	1.5	73	1	0.0017	10	10	0.071	0.006	$PM_{1.0}$	1.117	0.0268
									$PM_{10.0}$	1.906	0.0458
C6	1.5	73	1	0.0017	10	10	0.071	0.006	$PM_{1.0}$	1.108	0.0265
									$PM_{10.0}$	2.536	0.0609
C7	2	76	1	0.0017	10	10	0.071	0.004	$PM_{1.0}$	0.989	0.0237
									$PM_{10.0}$	2.12	0.0510
C8	2	78	1	0.0017	10	10	0.071	0.003	$PM_{1.0}$	1.85	0.0445
									$PM_{10.0}$	2.635	0.0634
C9	2	74	1	0.0017	10	10	0.071	0.006	$PM_{1.0}$	1.512	0.0363
									$PM_{10.0}$	2.267	0.0544
C10	1	70	1	0.0017	10	10	0.196	0.002	$PM_{1.0}$	1.209	0.0105
									$PM_{10.0}$	2.086	0.0180
C11	1	71	1	0.0017	10	10	0.196	0.003	$PM_{1.0}$	1.689	0.0146
									$PM_{10.0}$	2.439	0.0211
C12	1	75	1	0.0017	10	10	0.196	0.005	$PM_{1.0}$	1.418	0.0122
									$PM_{10.0}$	2.387	0.0206
C13	1.5	78	1	0.0017	10	10	0.196	0.003	$PM_{1.0}$	1.154	0.0100
									$PM_{10.0}$	1.736	0.0150
C14	1.5	72	1	0.0017	10	10	0.196	0.005	$PM_{1.0}$	2.133	0.0184
									$PM_{10.0}$	2.119	0.0183
C15	1.5	73	1	0.0017	10	10	0.196	0.004	$PM_{1.0}$	2.686	0.0232
									$PM_{10.0}$	3.39	0.0293
C16	2	75	1	0.0017	10	10	0.196	0.004	$PM_{1.0}$	2.641	0.0228
									$PM_{10.0}$	3.393	0.0293
C17	2	78	1	0.0017	10	10	0.196	0.002	$PM_{1.0}$	6.123	0.0530
									$PM_{10.0}$	6.555	0.0568
C18	2	80	1	0.0017	10	10	0.196	0.001	$PM_{1.0}$	5.436	0.0471
									$PM_{10.0}$	5.112	0.0443

For this research, health implications in laser paint removal process were evaluated based on the $PM_{1.0}$ and $PM_{10.0}$ concentrations released in provided wood box. The results show both types of $PM_{1.0}$ and $PM_{10.0}$ concentration detected during the laser paint removal process were far exceed from the recommended values suggested by WHO which were 99.3% and 99.4%, respectively. The lowest $PM_{1.0}$ and $PM_{10.0}$ concentrations detected during 10 minute laser irradiation were 0.693 mg/m^3 and 1.586 mg/m^3 as shown in Table 5. However, the recommendation suggested by WHO for 24-hour mean concentrations was 25 x 10^{-3} mg/m^3 for $PM_{2.5}$ and 50 x 10^{-3} mg/m^3 for $PM_{10.0}$ as shown in Table 4 (Krzyzanowski & Cohen, 2008; WHO, 2006). There was no specific guideline for $PM_{1.0}$ carried out from WHO, but the recommended mean concentration value for this

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particulate type should be less than 25 x 10^{-3} mg/m^3 for short term exposure.

Nevertheless, the scientific recommendation for interim target values of PM from WHO was done in open air which based on the selected certain cities in the world, not in the workplace. In addition, the health risk due to hazardous PM is considered to highly dependent on the air exchange in the workplace, the size of the workplace, the way of spreading, distribution, compositions and types of the PM itself. There should have the threshold limit value (TLV) in the workplace as suggested by Kusch et al. (2003), which was 6 mg/m^3 for totally independent of the chemical compositions of respirable dust (Kusch, et al., 2003).

But, there were no previous studies carried out regarding to the relationship between the size of workplace with the concentrations and distributions of PM released. For this study, the measurement of PM was done in restricted wood box for maximum detection of PM, and at the same time to protect the operators. Hence, the PM results obtained were not indicates the general health risk of laser paint removal process.

Moreover, the study from Ostrowski et al. (2007) suggested that laser irradiation generated air contaminants was usually toxic, allergic, carcinogenic and can caused severe disease after many years of exposure (Ostrowski, et al., 2007). Since the chemical compositions of PM released during the laser paint stripping process was not clearly known and its concentration was very high, detailed precaution and protection to the staff incharged should be strictly considered.

However, laser paint removal techniques was considered safe compared than chemical paint stripping technique if smooth air ventilation in workplace was properly set-up and inhalation to PM was greatly prevented by using protective mask. Conversely, chemical paint stripping process was intractable in prevention the health implications to the staff incharged due to continuous production of hazardous chemicals component as by-products sort of methylene chloride, phenolic compounds, activated acids, bases free from phenols and chromates and many more (Malavallon, 1995; Razab, et al., 2014c; Razab, et al., 2014e).

Directly exposed to these hazardous chemicals will be resulted in severe health implications. Moreover, chemical based stripping also generated large volume of hazardous waste which threatening the environment sustainability (Pole et al., 2006; Walters, et al., 1998). Due to this, laser paint removal technique seems to offer more reliable solutions compared to chemical paint removal process in term of health implications prevention in automotive industry.

4. Conclusion

There are no threshold concentration of PM proposed due to unable to define a threshold below an adverse effects expected. However, laser paint removal techniques was considered safe compared than chemical paint stripping technique if smooth air ventilation in workplace was properly set-up and inhalation to $PM_{1.0}$ and $PM_{10.0}$ was greatly prevented by using protective mask. Conversely, chemical paint stripping process was intractable in prevention the health implications to the staff incharged due to continuous production of hazardous chemicals component. Thus, laser paint removal technique is considered safe compared to conventional chemical stripping process in term of health implications prevention and safety managements.

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