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PARTICULATE RESUSPENSION DURING THE USE OF VACUUM CLEANERS ON OFFICE CARPETS IN UNIVERSITI MALAYSIA TERENGGANU

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Abstract: The household activities such as vacuuming may elevate the concentration of particulate matter in indoor environments. Cleaning workers and occupants inside closed room may be exposed to the fine particulate matter and at risk of developing numerous respiratory symptoms. This study aims to determine the concentration of the particulate matter (PM_{10} and $PM_{2.5}$) that might arise during vacuuming activities and estimated the surface compartmental residence time of particulate matter in indoor environment after each vacuuming activities. The PM_{10} and $PM_{2.5}$ concentrations throughout vacuuming were measured in forty-seven offices in Universiti Malaysia Terengganu using the TSI Dust Track DRX. Based on the concentrations measured, the surface compartmental residence time was then estimated using standardized equations taken from literature. The result shows that highest particulate matter concentration was nearly eleven times higher than the World Health Organization guidelines of 25 μg/m^3 for $PM_{2.5}$ concentration ($PM_{2.5}$ was 270 μg/m^3, PM_{10} was 421 μg/m^3), while the particulate matter were estimated to remain lingers inside the air for around 1-4 days before being deposited on the surface. In conclusion, the usage of vacuum cleaners may contribute to more particulate matter being released inside the air due to the resuspension phenomenon. Therefore, it is important for the occupants to maintain proper ventilation after each vacuuming activities took place.

Keywords: Particulate matter, particle resuspension, vacuum cleaners, $PM_{2.5}$, PM_{10}

Introduction

Adults and especially children are exposed to particulate matter (PM) every day from the flooring and other horizontal surfaces in their offices and homes. The National Human Activity Pattern Survey indicated that people spend about 87% of their time indoors (Klepeis *et al.,* 2001). However, spending time indoors can also expose human to high PM concentrations. Studies conducted to examine the effect of specific human activities on indoor PM concentrations have found that human activities such as dusting, walking, general cleaning and vacuuming has proven to dramatically increased the PM concentrations in indoor air (Ferro *et al.,* 2004; Qian *et al.,* 2008; Oberoi *et al.,* 2010; Lewis *et al.,* 2018).

Particulate resuspension is defined as particles or dust that deposited as settled dust, however were re-suspended again into the air due to external actions to include surface excitation, mechanical means and fluid flow (Corsi *et al.*, 2008; Qian *et al*., 2014; Lewis *et al.,* 2018). Smaller particles tend to be deposited earlier compared to larger size particles. Larger size particles have higher detachment fractions at lower shear velocities, therefore tend to be resuspended more compared to the smaller size particles (Corsi *et al.,* 2008; Qian *et al*., 2014). Although it has been reported that PM with larger aerodynamic diameter (greater than 30 μm) may be filtered naturally through human nasal breathing filtration that includes nasal hair and mucus lines in the nose, concerns are placed to the smaller particles that deposited further in the human respiratory tract (WHO 1999; Brown *et al.,* 2013). Thoracic fraction particles are usually penetrating beyond the larynx in the tracheobronchial region (median diameter of less than 12 µm) while respirable fraction particles (diameter less than 4 µm) usually passes the pulmonary where the gas-exchange region took place in the lungs and may directly absorbed by the blood (WHO 1999; Brown *et al.,* 2013; Noto *et al.,* 2016). Studies have shown that different size of particles with different deposition may induced different diseases (Morgan, 1978; Brown *et al.,* 2013).

Numerous studies have shown that indoor activities such as cooking, smoking, walking, cleaning and candle burning were found to be the major contribution to PM in indoor environment (Ferro *et al.,* 2004; Corsi *et al.*, 2008; Qian *et al*., 2014). Cleaning activities such as vacuuming has proven to increase PM concentration in indoor air due to resuspension of particles from the floor and PM generated from the mechanical motor and exhaust of the vacuum cleaner (Rosati *et al.,* 2008; Wu *et al.,* 2012). Studies shown that vacuum cleaning activities contributed to about 1.2 times to 29.5 times higher concentration of PM in indoor environment compared to background (Thatcher & Layton, 1995; Afshari *et al.,* 2005; Corsi *et al.*, 2008). As dust contains numerous allergens, heavy metals and pesticides (Knibbs *et al.,* 2012), the inhalation of dust may lead to respiratory disorders to include bronchitis, asthma, wheeze and organic dust toxic syndrome (Frankel *et al.,* 2012; Jimoda, 2012). Apart from being inhaled directly by adults and children, these particles may be deposited on the harder surfaces such as tables and toys and may be directly ingested by children and adults (Oomen & Lijzen, 2004; Rosati *et al.,* 2008).

In Universiti Malaysia Terengganu (UMT), the job task of cleaning workers will include two to three times of vacuuming episodes each week. These activities took approximately around four to fifteen minutes in each room, with around 25 to 30 rooms to be completed each day. Short-term exposure effect to indoor dust has been well documented to include allergy and respiratory diseases (Frankel *et al.,* 2012). One-hour exposure to PM_{10} (PM less than 10 µm in size) has been shown to be associated with asthma symptoms, while four hours exposure to $PM_{2.5}$ (PM less than 2.5 µm in size) has been shown to decrease heart rate variability in elderly patients (Tetre *et.al.,* 2002; Adhikari *et al.*, 2016). The workers may be at risk of developing numerous health problems associated with dust exposure in later stage of their life. Concerns were placed to these workers and occupants inside the rooms that may be exposed to PM that resuspended during vacuuming activities that they might not be aware of. Therefore, this study aims to determine the concentration of the PM (PM_{10} and $PM_{2.5}$) that might arise during each vacuuming activities and at the same time estimated the PM surface compartmental residence time inside the room.

Materials and methods

Measurements of Particulate Matter

The present study was conducted inside 47 private office rooms in UMT. Private office rooms with an approximately similar in size (area of $20m^2$) located in five different buildings were chosen using a purposive sampling method. In brief, the five buildings are namely Pusat Pendidikan Asas dan Liberal (PPAL), Kabin Biru, Pusat Pengajian Pembangunan Sosial dan Ekonomi (PPPSE), Pusat Pengajian Perniagaan dan Pengurusan Maritim (PPPM) and Pusat Pengajian Informatik dan Matematik Gunaan (PPIMG).

In short, the concentration of particulate matter (PM_{10} and $PM_{2.5}$) were measured using the TSI Dust Track DRX 8533, located in the middle of the room with 1.5 metres from the floor. The measurements of PM_{10} and $PM_{2.5}$ were taken before, during and after each vacuuming activities. In each measurements, careful considerations were taken by the researcher that other activities must not occurs during vacuuming and the windows and doors must be closed to minimise the penetration of outdoor air indoors, that would leads to the arising of particulate matter concentrations in the air. It is to make sure that the PM_{10} and $PM_{2.5}$ concentrations are only from the resuspension of particulate matter, not originating from other sources inside the room. In this study, the Industrial Vacuum Europower VAC-5001 was used as a vacuum cleaner in each of the rooms. The data collection was then conducted in between November 2018 to April 2019.

Estimating Surface Compartmental Residence Time of Indoor Particles

The surface compartmental residence time is defined as the average time a particle stays on surfaces before it is removed by surface cleaning (Qian *et al.,*2008). The surface compartmental residence time of indoor particles were calculated using a specific formula (Equation 1 and 2) developed by Qian and colleagues (Qian *et al.,* 2008). In this calculation, it is assumed that the air exchange rate is at standard rate (0.22 hr^{-1}) and the vacuuming activity is conducted while the room door is closed. Therefore, penetration from outdoor to indoor air would most likely not happen. The resuspension rate of $5 \times 10^{-5}\ hr^{-1}$ were used, the fractions of species removed was set to 0.05 hr^{-1} (Qian *et al.,* 2008), while the vacuumed area is default to $20m^2$, an approximate size of private rooms in UMT. Lastly, the vacuum time per unit area (in hour) was calculated by dividing the time taken for each vacuuming activities by the vacuum area.

The surface compartmental residence time is:

$$T = \frac{1}{n+r} \qquad \text{Equation 1}$$

$$n = \frac{\text{fraction of species removed}}{\textit{vacuumed area x vacuum time per unit area}}$$

Equation 2

where;

Resuspension rate, $r = 5 \times 10^{-5}\ hr^{-1}$, n = overall removal rate by vacuum cleaning (hr^{-1})

Results and Discussion

Particle Mass Concentration Profiles

Particle mass concentration profiles for both $PM_{2.5}$ and PM_{10} were generated for each room. The typical profiles generated is shown in Figure 1. In general, all rooms measured shows a lower background concentration of both $PM_{2.5}$ and PM_{10} before each vacuuming activities and followed by a sudden sharp increase of PM ($PM_{2.5}$ and PM_{10}) during vacuuming activities (PM_{10} increased from background of 51 $\mu g/m^3$ to 136 $\mu g/m^3$; $PM_{2.5}$ from 46 $\mu g/m^3$ to 96 $\mu g/m^3$). Post vacuuming activities shows that PM_{10} and $PM_{2.5}$ concentrations begun to decrease slowly after each vacuuming activities (Highest peak of PM_{10} decreased from 170 $\mu g/m^3$ to 110 $\mu g/m^3$; Highest peak of $PM_{2.5}$ decreased from 124 $\mu g/m^3$ to 80 $\mu g/m^3$).

In brief, this study has found that larger particles (PM_{10}) tend to resuspends more compared to smaller particles ($PM_{2.5}$), very similar to a study conducted by Corsi and colleague (2008) in Texas. These were due to the particles deposited as settled dust become resuspended into indoor air, where larger particles have higher tendency to being re-emitted and smaller particles tend to fall deeper inside the carpets (White & Dingle, 2002; Corsi *et al.,* 2008; Qian *et al*., 2014). In the said study, Corsi et al., (2008) identified the resuspension of particles during vacuuming by the sudden arise of particulate matter (peak) when compared to the background concentrations. Comparably, this study observed similar pattern. This suggested that vacuuming activities in UMT has positively contributed to the particle's resuspension in indoor environment.

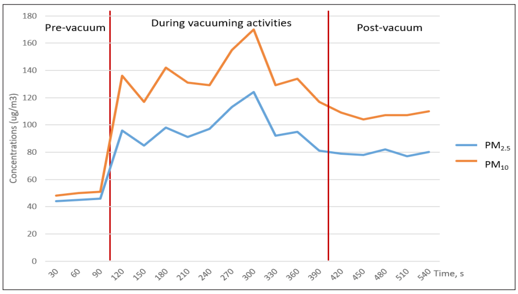

Figure 1: Particle mass concentration profiles (Room No 4)

$PM_{2.5}$ and PM_{10} Concentrations by Location.

Figure 2 shows both $PM_{2.5}$ and PM_{10} concentrations according to each building. The peak PM_{10} concentration during vacuuming ranged from 103 to 421 µg/m^3, nearly twice compared to the peak $PM_{2.5}$ concentration of only 70 to 270 µg/m^3. Comparing both PM concentrations according to each building, the PPIMG building shows the highest peak compared to PPAL, Kabin Biru, PPPSE and PPPM. This indicated that vacuuming activities in PPIMG building resuspended higher both PM_{10} and $PM_{2.5}$ concentrations (PM_{10} which was 421 µg/m^3 and $PM_{2.5}$ was 270 µg/m^3) compared to other buildings measured in this study. PPAL, Kabin Biru, PPPSE and PPPM indicated a lower peak of both PM_{10} and $PM_{2.5}$ respectably (PPAL, 156 µg/m^3, 95 µg/m^3; Kabin Biru, 105 µg/m^3, 83 µg/m^3, PPPSE, 103 µg/m^3, 72 µg/m^3 and PPPM, 109 µg/m^3, 70 µg/m^3). Concentrations differed significantly across buildings for both $PM_{2.5}$ and PM_{10} ($P<0.001$).

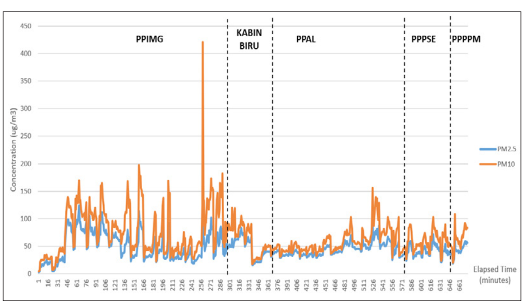

Figure 2: $PM_{2.5}$ and PM_{10} real-time concentrations distribution in five different buildings

The resuspension of $PM_{2.5}$ and PM_{10} may be affected by several factors to include the type of flooring, activity type and intensity, vacuum type, ventilation and relative humidity (Corsi *et al.*, 2008; Qian *et al.,* 2008; Rosati *et al.,* 2008; Qian *et al.,* 2014; Lewis *et al.,* 2018). Highest $PM_{2.5}$ and PM_{10} peak generated during vacuuming in PPIMG building may be explained by the type of flooring and the intensity of vacuuming. Carpet with different types of materials (fibers) may possess different types of micro-roughness (Mukai *et al.*, 2009; Goldasteh *et al.,* 2011). Mukai *et al.,* (2009) indicated that the difference in micro surface roughness are likely to affect resuspension. The carpet composed of high surface roughness are most likely to resuspence dust higher due to the air turbulence affect close to the surface., compared to softer types of carpet (Mukai *et al.*, 2009). Based on the observation, most private offices in PPIMG composed of hard carpets, therefore it might justify the highest peak of both PM_{10} and $PM_{2.5}$ measured in this study.

Although the rooms under PPAL building possesses approximate similar type of carpet, the slightly lower concentrations measured may be explained by the frequency and intensity of vacuuming (time gap) in each building. At the time of sampling, the vacuuming frequency in PPAL building was conducted twice monthly compared to only once in a month for offices in PPIMG building. Higher frequency of vacuuming has resulted to lower peak of both PM_{10} and $PM_{2.5}$ concentrations in PPAL compared to PPIMG building (PM_{10} peak of 156 µg/m^3, $PM_{2.5}$ peak of 95 µg/m^3 in PPAL vs. PM_{10} of 421 µg/m^3 and $PM_{2.5}$ of 270 µg/m^3). A study conducted by Ocak *et al.,* (2012) has shown that vacuuming activities conducted regularly every week may minimised the number of particles available for resuspension (Ocak *et al.,* 2012). This was also supported by the US EPA report, proving that a well-maintained carpet released less PM mass compared to a poorly maintained carpet (US EPA, 2007).

On the whole, the relatively lower values of particles resuspension concentration in other buildings can be well explained by the difference in surface roughness. Thus, other building consists of a mixture of mostly rough and soft carpets, therefore the concentrations are varies and slightly lower.

Estimation of Surface Compartmental Residence Time

Table 1 shows the total overall removal rate, (n) and surface compartmental residence time in days calculated from the stated formula developed by Qian *et al.,* 2008. The result shows that the average time particle particles linger in the air before it was removed by surface cleaning or resuspension was between 1 to 4 days, much lower compared to 19 days in a study conducted in New York (Qian *et al.,* 2008). The lower value in this study may be the result of smaller surface area ($20m^2$) compared to the New York study ($66m^2$) (Qian *et al.,* 2008) and higher rates of air exchange in Malaysia. The penetration of outdoor-indoor air after each vacuuming activity took place may help to lower the PM concentration inside the room, thus causing the PM to settle rapidly. The size of the room, the penetration of indoor-outdoor air and types of vacuums are few factors that might influenced the time taken for particles to settle down (Corsi *et al.,* 2008; Qian *et al*., 2008; Qian *et al*., 2014; Lewis *et al.,* 2018). As it is not clear how much vacuum cleaner may elevate or induced resuspension, more studies should be conducted using different types of vacuum cleaner for a better understanding of the mechanism. This would help researchers to invent vacuum cleaners that emitted less particles for better health.

Table 1: Total overall removal rate and surface compartmental residence time

Room No.	Time (min)	Overall removal rate (n)	Surface compartmental time (day)
1	11	0.27	4
2	6.5	0.46	2
3	8	0.37	3
4	9.5	0.31	3
5	7.5	0.40	3
6	10	0.30	3
7	5	0.60	2
8	5.5	0.54	2
9	8	0.37	2
10	7.5	0.40	3
11	5.5	0.54	2
12	7.5	0.40	3
13	9.5	0.31	3
14	5.5	0.54	2
15	5	0.60	2
16	6	0.50	2
17	8	0.37	2
18	8	0.37	3
19	9.5	0.31	3
20	5.5	0.54	2
21	7	0.42	2
22	9	0.33	3
23	6	0.50	2
24	4	0.75	1
25	6.5	0.46	2
26	5	0.60	2
27	5	0.60	2
28	6	0.50	2
29	4	0.75	1
30	4.5	0.66	1
31	10	0.30	3
32	10.5	0.29	3
33	9.5	0.32	3
34	10	0.30	3

cont.

35	6	0.50	2
36	6.5	0.46	2
37	5	0.60	2
38	9	0.33	3
39	9.5	0.32	3
40	7.5	0.4	3
41	7.5	0.4	3
42	7	0.43	2
43	6	0.50	2
44	4.5	0.67	2
45	5.5	0.55	2
46	9	0.33	3
47	6.5	0.46	2

Conclusion

This study found out that vacuum activities significantly increase the $PM_{2.5}$ and PM_{10} concentrations in indoor air with larger particles (PM_{10}) tend to resuspends more compared to smaller particles ($PM_{2.5}$). Factors such as type of carpets and vacuuming frequency also plays an important impact to increase the PM concentrations during vacuuming. As PM may lingers an average between 1-4 days, it is advisable for occupants inside closed rooms to allow windows to open after each vacuuming activities to avoid short-term health effect such as sneezing, coughing and running nose.

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