Characterization, Fate, and Re-Suspension of Aerosol Particles (0.3–10 µm): The Effects of Occupancy and Carpet Use

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ABSTRACT
In this study we present the particle number size distribution (diameter 0.3–10 µm with 1-minute time resolution) inside four offices (naturally ventilated) inside two university buildings. Each office had a typical environment in terms of occupancy and furniture. We focused on the differences between workdays and weekends in terms of particle number (PN) and particle mass (PM, assuming spherical particles with unit density) concentrations. Moreover, we illustrated the effect of workers’ activity (occupancy, smoking, etc.). We also applied a simple indoor aerosol model to estimate the fate (gravitational settling and exfiltration) and source strength of aerosol particles within the measured particle size range. During workdays, the highest measured 24-hour average PM10–1 in the occupied office was 41.5 µg m–3 (PN10–1 = 2.2 cm–3) compared to 9.0 µg m–3 (PN10–1 = 1.2 cm–3) in the unoccupied offices. The ventilation rate of the offices that were opposite to each other was about 0.15 h –1 whereas it was 0.28–0.38 h –1 for the other offices, which were a bit distant from each other. The gravitational settling analysis suggested that a suitable particle density ($\rho_p$) could be ~1.7 g cm –3 with a shape factor $\chi$ ~1.57, which is similar to mineral dust particles. The gravitational settling rate of particles around 2 µm in diameter was about 0.3 h –1. The source strength of indoor dust particles was higher in the occupied and carpeted offices (re-suspension emission rate as high as 235 µg m–3 h–1) in comparison to unoccupied and uncarpeted offices (75 µg m–3 h–1). This study provided us with an insight about the effect of occupancy and carpet use on the dynamic behavior (fate and re-suspension) of dust particles inside university office buildings located in semi-arid regions.

Keywords: Indoor air quality; Particle number size distribution; Particulate matter; Aerodynamic diameter; Gravitational settling.

INTRODUCTION
The World Health Organization (WHO) implemented the right of healthy indoor atmosphere (WHO, 2000); and then estimated the annual deaths of about 1.5 million people due to improper indoor air quality (WHO 2007). Accordingly, both indoor air quality (IAQ), indoor exposure, and occupational health have been the highlight of many studies owing to the fact that people spend more than 90 % of their time indoors (e.g., McCurdy et al., 2000; Klepeis et al., 2001; Schweizer et al., 2007; Hussein et al., 2012).

In general, the IAQ has been correlated with performance efficiency of workers (e.g., Wargocki et al., 2000; Mendell and Fisk, 2007). In fact, it is considered of extreme importance to develop methodologies that provide healthy indoor environments and reduce exposure to harmful particulate matter both indoors and outdoors (e.g., Gerharz et al., 2013; Hanninen et al., 2014; Hussein, 2015). For instance, De Gennaro et al. (2014) reviewed some practical approaches used to improve the IAQ at schools in terms of building materials, furnishing, cleaning, personal hygiene products, and personal lifestyles. Similar approaches include potential indoor aerosol sources that are commonly used like printing practices, cigarette smoke, dust re-suspension, etc. (He et al., 2004; Ren et al., 2006; Morawska et al., 2009; Koivisto et al., 2010; Sangiorgi et al., 2013).

Indoor aerosols could be of either outdoor or indoor origin. Those originating outdoors penetrate/infiltrate into indoor environments as a result of the air exchange processes, which depends mainly on the building characteristics and ventilation method. Indoor sources of aerosols are closely linked to human behavior. Eventually, indoor aerosols are removed by dry deposition or through the indoor-outdoor air exchange (such as exfiltration). Moreover, the influence of ventilation on the IAQ of offices has been one of the first and most studied parameters (e.g., Turiel et al., 1983; Godish and Spengler, 1996; Spengler and Chen, 2000; Quang et al., 2013). Furthermore, human mechanical activities indoors

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increase the concentration of particles by re-suspending them to become airborne again. Hence, the attention is drawn towards school gyms and children care centers (e.g., Ferro et al., 2004; Buonanno et al., 2012).

Even though many studies have investigated the IAQ inside a wide range of indoor environments, only few have been directed towards work environments, and even fewer towards educational classrooms and offices (Diapoulis et al., 2008; Gaidajis and Angelakoglou, 2009; Tran et al., 2012; Salma et al., 2013). Besides that, the focus on the dynamic behavior and exposure to large particles has not been given sufficient attention inside such indoor environments. Furthermore, measurement and characterization of particles emitted in offices due to workers’ activities, such as occupancy, physical movement and lifestyle, are rather few and require more attention. The importance of studying coarse particles comes from the fact that they are related to increased asthma and other respiratory and health problems (e.g., Brunekreef and Forsberg, 2005). Coarse particles are also known to be associated with the spreading of infections and the accommodation of many airborne bacterial species (Fox et al., 2005).

In this study we measured the particle number distributions (optical diameter 0.3–10 µm, 1-minute time resolution) inside four offices located in two educational buildings. The offices were naturally ventilated: two were carpeted and occupied regularly and the other two were unoccupied and not carpeted. We focused on (1) differences between workdays and weekends in terms of particle number (PN) and particle mass (PM) concentrations and (2) the effect of workers’ activity (occupancy, smoking, moving, etc.) on both PN and PM of different particle size fractions. We also utilized a simple indoor aerosol model to estimate the gravitational settling rate, ventilation rate, and sources strength of dust particle re-suspension inside each office. This study is an extension of a previous one, which presented the PN and PM of different particle size fractions inside one of the offices discussed here (Hussein, 2015). Here, three more offices were included and we utilized more extensive data analysis and modeling in order to understand the dynamic behavior dust particles indoors.

**MATERIALS AND METHODS**

**Indoor Environments and Site Location**

The indoor measurement campaign was performed during September 18–November 17, 2013 followed by an outdoor air measurement campaign during November 20–December 3, 2013 at the University of Jordan campus. The campus is located in a suburban area at about 15 km northwest the city center Amman, Jordan. It is surrounded by a residential area mixed with urban forest and main streets.

The indoor environments were four offices (Figure Map): Offices A1 and A2, each with two panoramic windows, were located on the first floor of the Faculty of Science building whereas Offices B1 and B2, each with only one window, were located on the second floor of the Department of Physics building. The offices were naturally ventilated at all times; both buildings were not equipped with mechanical ventilation system.

The Faculty of Science building was a two-floor construction with the main entrance located in the middle leading to the stairways that divide the building into two unsymmetrical halves. During the working hours, the main door of the building as well as the offices’ windows and doors were all opened. Measurements were performed inside Offices A1 (4.8 × 3.4 × 2.9 m³) and A2 (5.6 × 3.6 × 2.9 m³) during September 18–October 1 and October 1–15, respectively. Each office was occupied by one worker. Office A1 seldom had visitors and students whereas office A2 often had visitors. Besides typical office furniture, these offices were carpeted.

Neighboring the Faculty of Science building is the Department of Physics building. Both offices B1 and B2 were on the second floor of the Department of Physics building and opposite to each other. The building is a three-floor construction with several entrances. Measurements were performed inside Office B1 (5.1 × 2.9 × 2.8 m³) during October 24–November 4 and inside office B2 (5 × 2.9 × 3.2 m³) between November 5 till 17. These offices were vacant except for brief periods that did not exceed 10% of the total measurement time. Contrary to A1 and A2, offices B1 and B2 were not carpeted, yet still contained typical office furniture.

When offices were closed, the outdoor air could easily infiltrate into the indoor air across the window frames and through the narrow slaps under the doors. Even though smoking is prohibited inside the buildings, workers/visitors often ignored regulations and smoked in other offices on the same floor.

Outdoor measurement campaign was performed on the third floor (about 11 m from ground) of the Department of Physics by directly sampling the outdoor aerosols via a copper tube (~0.4 cm inner diameter and about 1 m long extended outside the window). These measurements were performed to investigate the temporal variation and the order of magnitude of the outdoor particle concentrations. Although it would have been more reliable to have the indoor and outdoor measurements performed in parallel, this was not possible due to the instrument limitations.

**Aerosol Measurements**

The particle number size distribution (optical diameter 0.3–10 µm, 13 size-bins) was measured with an Optical Particle Sizer (TSI OPS 3330). The temperature and pressure were also recorded by the same instrument. The OPS was set to measure the particle number size distributions with the dead-time correction applied. The sampling time-resolution and flow rate were 1 minute and 1 L min⁻¹, respectively. Indoor air was sampled directly without additional tubing at a height of about 1.6 m as it represents the breathing zone of the worker. The instrument was calibrated by the manufacturer three months prior to the measurement campaign.

**Aerosol Data Handling**

The measured particle number size distributions were quality checked. 100% of the measured data was valid, processed, and analyzed. Averages of 5-minute intervals were processed, and analyzed. Aver ages of 5-minute intervals were processed, and analyzed. Aver ages of 5-minute intervals were processed, and analyzed. Aver ages of 5-minute intervals were processed, and analyzed.
were calculated and illustrated along with 30-minutes or hourly averages. 24-hour averages as well as daytime (9:00–17:00) averages were also calculated and reported.

The particle mass size distributions were calculated assuming spherical particles with unit density. Even though these assumptions were not totally correct, a lower estimate for the PM concentration level inside the offices is favored. Besides that, the PM_{10} is also underestimated as the aerosol measurements did not cover particles smaller than 300 nm in diameter.

Throughout this article we shall present the particle number (PN) concentration and the corresponding particle mass (PM) concentration of the coarse fraction (particle diameter between 1 and 10 µm, PM_{10–1}) and a part of the fine fraction (particle diameter between 0.3 and 1 µm, PM_{0.3–1}). The concentrations of these particle size fractions were obtained by integrating the particle size distributions over the specified particle size range.

**Fate and Particle Loss Rate**

The dynamic behavior of indoor aerosols can be described by the mass-balance equation (e.g., Hussein and Kulmala, 2008)

\[
\frac{dI}{dt} = P\lambda O - \lambda I - \lambda_d I + Re
\]

(1)

where the left-hand-side represents the change rate of indoor aerosol particle concentrations (either mass or number concentration) and the right-hand-side represents the dynamic processes that are involved in indoor aerosols. According to our setup, we considered the indoor-outdoor air exchange (the first two terms: \( P \) is penetration factor, \( \lambda \) is ventilation rate, \( O \) is outdoor concentration, and \( I \) is indoor concentration), dry deposition (third term: \( \lambda_d \)), and re-suspension (fourth term: \( Re \)).

In general, the removal of indoor aerosol particles occurs via the indoor-outdoor air exchange and dry deposition onto indoor surfaces. The particle loss rate of indoor aerosols can be quantified by following indoor aerosol concentration decay right after being emitted/re-suspended during an indoor activity (e.g., Hussein, 2015). The logarithm of the concentrations versus time follows a line with a negative slope. The slope is, in fact, equivalent to the particle loss rate

\[
\lambda + \lambda_d = \frac{1}{\Delta t} \ln \left( \frac{I(t_0)}{I(t)} \right)
\]

(2)

where \( \lambda \) [h\(^{-1}\)] is the ventilation rate, \( \lambda_d \) [h\(^{-1}\)] is the deposition rate of aerosol particles onto available indoor surfaces, and \( \Delta t \) [h] is the time interval \( t - t_0 \) for the concentration decrease from \( I(t_0) \) to \( I(t) \). This equation is valid when there are no indoor sources and the outdoor concentrations are very small when compared to the corresponding ones indoors.

Recalling that aerosol particles within the diameter range 0.1–1.0 µm have the smallest deposition rate and it is usually much smaller than the ventilation rate (i.e., \( \lambda_d << \lambda \)), then Eq. (2) can be used as an upper estimate for the ventilation rate (Hussein et al. 2009).

**RESULTS AND DISCUSSION**

**Average Concentrations: Occupancy versus Vacancy**

In general, the 24-hour average concentration of the coarse fraction (PM_{10–1}) in the carpeted and regularly occupied offices A1 and A2 was higher on the workdays (Sunday–Thursday) than on weekends or holidays (Tables S1 and S2). For instance, during workdays, the 24-hour average PM_{10–1} was 37.3 µg m\(^{-3}\) and 41.5 µg m\(^{-3}\) in Office A1 and Office A2, respectively. On the other hand, during the weekend the averages were lower and varied within the range of 3.4–7.0 µg m\(^{-3}\) in Office A1 and 1.3–10.8 µg m\(^{-3}\) in Office A2. Similarly, during Eid holiday which started on Sunday October 13th, the PM_{10–1} in Office A2 was within the concentration range observed during the weekend.

The concentration differences between workdays and weekend/holidays were not observed in the uncarpeted and occasionally occupied Offices B1 and B2. The PM_{10–1} did not exceed 10 µg m\(^{-3}\) in Office B2. The situation in Office B1 was special due to a dust episode during October 29–31, which caused outdoor dust aerosols to infiltrate into the office and increase the 24-hour average PM_{10–1} to about 120 µg m\(^{-3}\) and the PN_{0.3–1} to about 111 cm\(^{-3}\).

As for the concentrations outdoors, the 24-hour average PM_{10–1} was 12.8–24.8 µg m\(^{-3}\) and 11.8–56.1 µg m\(^{-3}\) on workdays and weekends, respectively (Table S3). Excluding occupancy events in the offices, the 24-hour average PM_{10–1} outdoors were higher than those observed indoors. On the other hand, during working hours, the occupied offices (A1 and A2) show higher mass concentration indoors than outdoors, while the unoccupied offices (B1 and B2) show lower concentrations in comparison to outdoors.

Based on the half-hourly means and excluding smoking and dust event episodes, the PN_{0.3–1} (PM_{0.3–1}) varied between 15–205 cm\(^{-3}\) (1.5–190 µg m\(^{-3}\)) and 10–650 cm\(^{-3}\) (1–250 µg m\(^{-3}\)) in the carpeted and regularly occupied offices A1 and A2, respectively (Figs. 1 and 2). In the uncarpeted and occasionally occupied Offices B1 and B2, the PN_{0.3–1} (PM_{0.3–1}) varied between 22–195 cm\(^{-3}\) (2–75 µg m\(^{-3}\)) and 25–280 cm\(^{-3}\) (2–110 µg m\(^{-3}\)), respectively (Figs. 3 and 4).

While more than 98% of the PN_{0.3–1} comprised of particles smaller than 1 µm in all offices, the coarse fraction was about 85%, 78%, 80%, and 60% of the PM_{10–1} in Offices A1, A2, B1, and B2, respectively. Recalling the fact that most coarse particles are actually dust particles, the indoor air of carpeted Offices A1 and A2 contained more dust particles than the uncarpeted Offices B1 and B2. Therefore, we assume that carpets accommodate dust deposits more efficiently than bare floors (Layton and Beamer, 2009). Furthermore, occupancy and moving around inside an office increases the mechanical re-suspension of dust particles; and thus, increases the concentration of coarse particles indoors (Meyer et al., 1999).

These findings suggest that the occupants’ activities in Offices A1 and A2 increased the PN and PM concentrations (especially PN_{0.3–1} and PM_{0.3–1}) during the daytime (between 09:00–17:00). Similar result was observed in
Fig. 1. Time series based on the half-hourly averages of the measured particle number size distributions within the diameter range 0.3–10 µm inside Office A1: (a) integrated particle number concentrations, (b) integrated particle mass concentrations by assuming spherical particles with unit density, and (c) indoor air temperature and pressure. Smoking events occurred on 19 and 26 September which are clear with high concentration peaks on the PN_{0.3-10} curve.

Fig. 2. Time series based on the half-hourly averages of the measured particle number size distributions within the diameter range 0.3–10 µm inside Office A2: (a) integrated particle number concentrations, (b) integrated particle mass concentrations by assuming spherical particles with unit density, and (c) indoor air temperature and pressure. Short time occupancy occurred on 12 and 5 October which are clear with elevated concentrations. The last two days were Eid Holidays.
Fig. 3. Time series based on the half-hourly averages of the measured particle number size distributions within the diameter range 0.3–10 µm inside Office B1: (a) integrated particle number concentrations, (b) integrated particle mass concentrations by assuming spherical particles with unit density, and (c) indoor air temperature and pressure. Smoking event occurred on 3 November which is clear with high concentration peak on the PN$_{10,0.3}$ curve. Dust episode occurred during 29–31 October which is clear with elevated coarse fraction concentration.

Fig. 4. Time series based on the half-hourly averages of the measured particle number size distributions within the diameter range 0.3–10 µm inside Office B2: (a) integrated particle number concentrations, (b) integrated particle mass concentrations by assuming spherical particles with unit density, and (c) indoor air temperature and pressure. Short time occupancy occurred on 8, 10 and 16 November which are clear with elevated concentrations.
Offices B1 and B2 when the periods of occupation were compared to the periods of inoccupation. For example, the half-hourly average $\text{PN}_{10.0.3}$ ($\text{PM}_{10.0.3}$) did not exceed 80 cm$^{-3}$ (10 µg m$^{-3}$) when Office A2 was closed and unoccupied, but they were as high as 650 cm$^{-3}$ (250 µg m$^{-3}$) when it was occupied. The $\text{PN}_{10.0.3}$ ($\text{PM}_{10.0.3}$) did not exceed 20 cm$^{-3}$ (160 µg m$^{-3}$) when Office B2 was closed and unoccupied, but the concentrations were as high as 280 cm$^{-3}$ (110 µg m$^{-3}$) when the office was occupied.

There was no clear indication that the accumulation mode fraction ($\text{PN}_{1.0.3}$) is affected by occupancy in these offices as its concentration did not show major difference during working hours in comparison to other times. However, the same size fraction shows an increase in concentration due to smoking activities that happened in Office A1 (September 19 and 26) and in Office B1 (November 3) resulting in 24-hour average $\text{PN}_{1.0.3}$ increase. The smoking event which occurred in Office B1 was accompanied by the presence of 5 persons and resulted in 24-hour average $\text{PM}_{10.1}$ of around 32 µg m$^{-3}$ and $\text{PN}_{1.3}$ around 140 cm$^{-3}$ (Table S2). Similarly, the smoking events occurred in Office A1 increased both the $\text{PM}_{10.1}$ and $\text{PN}_{1.0.3}$ values as indicated in Table S1. Based on the half-hourly averages, smoking inside Office A1 increased the $\text{PN}_{1.0.3}$ ($\text{PM}_{10.0.3}$) to more than 4800 cm$^{-3}$ (3700 µg m$^{-3}$) (Fig. 1).

Our observations also suggest that the aerosol concentrations inside an occupied office is expected to exhibit a clear daily pattern that is similar to the one observed in the regularly occupied Offices A1 and A2 (Figs. S1 and S2); i.e., high concentrations during workdays daytime and low concentrations otherwise. Rarely occupied offices (such as B1 and B2) are expected to have a similar daily pattern of coarse particles on all days regardless of being a workday or a weekend. The daily patterns on weekends/holidays were similar for Offices A2 and B2 because their windows face the same outdoor area and on non-workdays the indoor aerosols are from outdoor origin. The daily patterns observed in Office B1 showed a similar behavior, but with lower concentrations and the peaks occurred with a slight delay, to those observed outdoors. This is because Office B1 outlooks to the same area where the outdoor measurement was performed.

It is important to remember that PM values were reported assuming spherical particles and unit density. Therefore, the actual gravimetric mass values of the coarse fraction ($\text{PM}_{10.0.3}$) are expected to be at least double the reported ones. In addition to that, the measured particle size diameter was larger than 0.3 µm, which suggests higher values for the $\text{PM}_{10.0.3}$. In fact, it is difficult to make a reasonable assumption for the $\text{PM}_{10.0.3}$ here due to the lack of information about the size distribution of the fine fraction smaller than 0.3 µm in diameter. As such, the 24-hours averages reported here easily exceed what is recommended by the WHO guidelines: 50 µg m$^{-3}$ for $\text{PM}_{10.0.3}$ and 25 µg m$^{-3}$ for $\text{PM}_{2.5}$.

The reported PM values in this study are also higher than those found in the literature regarding university buildings. For example, the day-to-day $\text{PM}_{10}$ variation inside a lecture hall at a university in Hong Kong showed a rather similar trend as that observed here for Offices A1 and A2 reflecting the high concentrations on workdays’ daytime and low concentration at nighttime and weekends (Salma et al., 2013). However, their reported $\text{PM}_{10}$ concentrations were as high as 100 µg m$^{-3}$ with median value of 15.3 µg m$^{-3}$, which is less than what is reported here for the occupied offices A1 and A2. The 24-hours concentrations of $\text{PM}_{10}$ and $\text{PM}_{2.5}$ varied between 59–220 µg m$^{-3}$ and 45–118 µg m$^{-3}$ in five classrooms, an office, and a meeting room located within a university building in Greece (Gaidajis and Angelakoglou, 2009), which indicates that the coarse fraction would be in the range 14–102 µg m$^{-3}$. The $\text{PM}_{10}$ concentrations in French occupied classrooms had weekly averages in the range 72.7–85.3 µg m$^{-3}$ and in unoccupied classrooms 13.2–24.8 µg m$^{-3}$ with a corresponding outdoor concentrations in the range 29.6–51 µg m$^{-3}$ and 23.1–29.3 µg m$^{-3}$, respectively (Tran et al., 2012). Diapouli et al. (2008) reported the 8-hour (between 08:00–16:00) $\text{PM}_{10}$ inside teachers’ office (carpet, high occupancy, and allowed smoking) at a primary school in Athens had a mean value of 229 µg m$^{-3}$, which is about double the mean value presented in this study.

As shown before in this section, the highest concentrations occurred during high occupancy with smoking events. Besides that, tobacco smoke particles remained in the indoor air for more than 20 min. This kind of observation has been well reported before (Ozkaynak et al., 1996; Slezakova et al., 2009; Guo et al., 2010; Salma et al., 2013). As an example, Afshari et al. (2005) showed that the fine particle number concentration and also particles larger than 1 µm suddenly increased to more than 10$^7$ cm$^{-3}$ and they stayed airborne for more than 100 minutes. Morawska et al. (2003) reported even higher concentration reaching 3.5 × 10$^8$ cm$^{-3}$ during tobacco smoking. Hussein et al. (2006) showed that smoking a cigarette in a living room increased the fine particle number concentrations to about 3.6 × 10$^4$ cm$^{-3}$ with a well-distinguished fine mode extending up to 600 nm. Similarly, He et al. (2004) reported fine particle number concentrations of about 2.7 × 10$^4$ cm$^{-3}$ during tobacco smoking.

**Particle Loss Rates**

**Gravitational Settling**

The particle losses ($k_1 + k_2$) in this study include dry deposition and exfiltration via natural ventilation. As described in the methods section, we can quantify aerosol particle losses by analyzing suitable occasions that meet the assumptions stated for Eq. (2). Such occasions occur right after the end of the working hours, when the offices were unoccupied and the concentration of indoor aerosols decreased after being at high levels during working hours. In general, it is sometimes preferred to describe the particle losses with respect to the aerodynamic diameter. The optical diameter ($D_{\text{optical}}$) is converted into aerodynamic diameter ($D_d$) by assuming that aerosol particles in the measured size range are mainly dust particles that have a density $\rho_p \sim 1.7$ g cm$^{-3}$ and shape factor $\chi \sim 1.57$ (Hinds 2012); i.e., $D_d = D_{\text{optical}} \sqrt{\frac{\rho_p}{\rho_w}}$, where $\rho_w$ is water density.

We should keep in mind that the measured concentrations...
in the lower particle size-bins of the Optical Particle Counter are not reliable. Therefore, we took this into account by omitting some of the lower-most size-bins as needed.

The loss rate \( (\lambda + \lambda_d) \) of particles in the diameter range 0.3–1 µm varied within 0.25–0.30 h\(^{-1}\) inside Office A1, 0.37–0.44 h\(^{-1}\) inside Office A2, and 0.09–0.20 h\(^{-1}\) inside Office B2 (Fig. 5). Due to limitation in the measurement setup and the aerosol data set obtained for Office B1, it was not possible to estimate the loss rate of particles smaller than 1 µm in diameter. In all offices, the particle loss rate \( (\lambda + \lambda_d) \) increased with the particle size for \( D_a > 1 \) µm. This finding is expected because the dominant dry deposition mechanism in that particle size range is gravitational settling.

The dry deposition rate \( (\lambda_d) \) is simply the ratio of the gravitational settling velocity \( (V_g) \) to the height \( (H \sim 3 \text{ m}) \) of the office; i.e., \( \lambda_d = V_g/H \). Based on these assumptions, we calculated \( V_g \) and plotted \( \lambda_d = V_g/H \) curve with an offset value to best-match the experimental curve of \( (\lambda + \lambda_d) \) (Fig. 5). The close match between the experimental curves of \( (\lambda + \lambda_d) \) and the calculated gravitational settling rate \( (\lambda_d = V_g/H) \) with the offset values indicates that our assumptions for the particle density \( (\rho_p \sim 1.7 \text{ g cm}^{-3}) \) and shape factor \( (\chi \sim 1.57) \) of the dust particles are acceptable. It is important to note that indoor dust include crustal material and soil brought from the outdoor air, biological material, and skin scales (Davies and Noble, 1962; Clark, 1974; Janssen et al., 1999; Avigo Jr et al., 2008; Fromme et al., 2008; Parker et al., 2008; Stranger et al., 2008) which is similar to the particle composition of our assumptions in this study. Salma et al. (2013) investigated the settling time of two types of dust particles: general indoor dust and chalk dust. According to their findings, general indoor dust particles settle within 34 minutes, which is about twice the time needed to settle chalk dust particles. It was previously reported that re-suspension and loss rates of particles (0.5–10 µm in diameter) is linked to the occupancy and the furnishing with an emphasis that coarse particles are the most affected by the occupancy and furnishing scheme (Thatcher and Layton, 1995, Thatcher, Lai et al., 2002). That was also confirmed in a mechanically stirred chamber for particles with diameters 0.7, 1 and 5 µm (Abadie et al., 2001).

**Exfiltration and Ventilation Rate**

The offset values reported in the loss rate analysis were 0.28 h\(^{-1}\), 0.38 h\(^{-1}\) and 0.15 h\(^{-1}\) for Office A1, Office A2 and Offices B1–B2, respectively. These offset values are basically an estimate for the ventilation rate \( (\tilde{\lambda}) \). The offices in the Department of Physics building were opposite to each other; and thus, their ventilation rate \( (\tilde{\lambda}) \) was similar: about 0.15 ± 0.06 h\(^{-1}\) and 0.15 ± 0.04 h\(^{-1}\) for Office B1 and Office B2, respectively. The offices located in the Faculty of Science building were on the same floor but in opposite sections of the floor. Therefore, the ventilation rate \( (\tilde{\lambda}) \) was 0.28 ± 0.03 h\(^{-1}\) and 0.38 ± 0.02 h\(^{-1}\) for Office A1 and A2, respectively. This result suggests that the ventilation rate \( (\tilde{\lambda}) \) for the offices located in the same building might

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**Fig. 5.** Particle loss rate \( \lambda + \lambda_d \) [h\(^{-1}\)] inside the offices. The lines represent calculated gravitational settling rate \( (\lambda_d = V_g/H) \) of aerosol particles with an offset value reflecting the average ventilation rate \( (\tilde{\lambda}) \) as indicated for each office.
exhibit rather similar ventilation rate, which reflects the characteristics of the building. Furthermore, the closer the offices are the more similar their ventilation rates.

The ventilation rates reported here for the offices are within the range found in literature for natural ventilation being less than 2 h⁻¹. For instance, Persily et al. (2005) presented the ventilation rates of 100 US office buildings for an EPA study and reported average ventilation rate in these offices of about 1 h⁻¹. The natural ventilation also for an EPA study and reported average ventilation rate in

presented the ventilation rates of 100 US office buildings had ventilation rates between 0.37 h⁻¹ and 1.52 h⁻¹ (Breen et al., 2010; Yamamoto et al., 2010). Some retail stores in the US were found to have ventilation rates around 1 h⁻¹ (Zaatari et al., 2014). On the European level, a review of measured natural ventilation rates in houses of different European cities reports values similar to those presented in this study ( Dimitrouloupoulou et al. 2012). Similarly, Hussein et al. (2005) reported an average value of ventilation rate ~0.34 h⁻¹ in a family house in Espo, Finland. Also, ventilation rates varied between 0.6 and 1.2 h⁻¹ when measured inside a house in Prague, Czech Republic ( Hussein et al., 2006).

In England, 37 naturally ventilated houses that were built since 1995 had a ventilation rate between 0.17 h⁻¹ and 0.51 h⁻¹ (Crump et al., 2005). In European schools, the values of ventilation rates seem to be higher than those reported in this study ( Wargocki et al. 2002). For instance, Smedje et al. (2000) reported rates in Swedish schools having an average around 3 h⁻¹. Similarly, Walinder et al. (1998) reported an average value around 1.9 h⁻¹.

Re-Suspension Emission Rate

Recalling the mass balance Eq. (1), it can be used to estimate the source terms (P\(\lambda\)O + Re) of indoor aerosols as

\[
\frac{d}{dt} I_{\text{meas}} + (\lambda + \lambda_{\text{d}}) I_{\text{meas}} = P\lambda O + \text{Re} \tag{3}
\]

Knowing that the coarse particles have a mode aerodynamic diameter around 3 µm, their gravitational settling rate (\(\lambda_{\text{d}}\)) is about 0.43 h⁻¹. Investigating the left-hand-side of this equation with respect to the measured indoor coarse aerosol concentration yields a characteristic relationship for the source terms (P\(\lambda\)O + Re) as shown in Fig. S3. For instance, Office B2 (the least occupied) shows a well-defined scatter around the best-fit line with only very few points that have positive residue values at high indoor aerosol concentrations (Fig. S3(d)). Office A2 (the most occupied) showed two clusters of scattered points: the first one with low indoor aerosol concentrations represent the un-occupancy periods whereas the second with high indoor aerosol concentrations (and positive residue values) represents the occupancy periods (Fig. S3(b)). This contrast between the two offices indicates that the data points with high indoor aerosol concentrations and positive residue values are most likely related to the re-suspension of indoor aerosols due occupancy and moving around inside the offices. This observation is also clear for Office A1 but not pronounced for Office B1 (Figs. S3(a) and S3(c)).

While the characteristic best-fit line represents most of the data points, we can interpret it in terms of the infiltration rate (P\(\lambda\)O) of outdoor coarse aerosols into the offices. As indicated in Fig. S3, the infiltration rate was the highest for Office A2 and the least for Offices B1 and B2. This finding is not a surprise since Offices B1 and B2 were closed most of the time whereas Office A2 was open for longer periods than Office A1.

Feeding in the infiltration term into the mass-balance Eq. (3) yields a rough estimate for the re-suspension source rate (Re) of coarse particles. For example, the re-suspension rate inside Office A2 was in the range 2–235 µg m⁻³ h⁻¹ whereas it was as high as 190 µg m⁻³ h⁻¹ inside Office A1 and less than 75 µg m⁻³ h⁻¹ inside Office B2 (Fig. S4). We should also keep in mind that these values are based on the assumption of spherical particles with unit density.

It has been very well known that coarse particles are the most affected by human movement that re-suspends them back in the indoor air (e.g., Ferro et al., 2004). For example, re-suspension is affected by human foot motion such as walking and foot tapping, which also redistribute particulate matter on a surface (Kubota and Higuchi, 2013). A strong correlation appears between the number of individuals and the particle re-suspension (Buonanno et al., 2012). Moreover, carpets are potentially more significant with higher re-suspension rates in comparison to smooth and bare floors (Shaughnessy and Vu, 2012). Usually, school gyms are the places where extensive activities are conducted and, as a result, re-suspension of aerosol particles is very well pronounced. Brans and Safranek (2011) showed that PM₁₀,₂₅ were 1.2–29.4 µg m⁻³ inside a school gym with indoor-to-outdoor (I/O) ratio was higher than two. In the same study, the I/O ratio was below 0.5 with the indoor PM₁₀,₂₅ varied between 0.5–4.9 µg m⁻³ during weekends and holidays. In another study, Buonanno et al. (2012) confirmed that the PM₁₀,₂₅ emission factors in the range of 1.5–8.9 mg min⁻¹ during exercising activities of pupils inside a school gym. These re-suspension rates were slightly higher than those presented by Ferro et al. (2004) as 0.03–0.5 mg min⁻¹ for PM₂₅, and 0.1–1.4 mg min⁻¹ for PM₁₀. The differences between Buonanno et al. (2012) and Ferro et al. (2004) are possibly due to the difference in the considered particle size range.

CONCLUSIONS

Indoor air quality in offices is currently one of the rising topics due to its effect on health and workers’ efficiencies. This study compared the workdays and weekend pattern of particle number (PN) and particle mass (PM) concentration in four offices in Jordan. We also investigated of the effect of occupancy on re-suspension of aerosol particles. Furthermore, we utilized a simple indoor aerosol model to estimate gravitational settling, ventilation rate, and re-suspension emission rate. First, human activities indoors result in mechanical re-suspension of dust particles and are accompanied with an increase in higher coarse particles concentrations. For instance, during workdays, the maximum measured 24-hour average PM₁₀₋₁ in the occupied office
was 41.5 μg m⁻³ (PN_{10-1} = 2.2 cm⁻³) compared to 9.0 μg m⁻³ (PN_{10-1} = 1.2 cm⁻³) in the unoccupied offices. This suggests that regularly occupied offices exhibit a daily pattern where high concentrations recorded during working hours and not otherwise. On the other hand, rarely occupied offices do not show a difference in the daily pattern of coarse particles during weekdays and weekends as these are only affected by particles infiltrating from outdoor.

Second, the presence of carpets is associated with higher particle concentration due to the ability to accommodate dust. Human activities, in terms of movement and smoking, inside the offices were shown to cause an increase on the particle mass concentration and number concentrations for a period of time up to 20 minutes.

Third, the ventilation rate of the offices that were opposite to each other was about 0.15 h⁻¹ whereas it was 0.28–0.38 h⁻¹ for the other offices, which were a bit distant from each other. The gravitational settling analysis suggested that coarse particles in these offices have a density ρ_p ~1.7 g cm⁻³ and shape factor χ ~1.57. Gravitational settling was found to increase with particle diameter. For instance, the gravitational loss rate for 2 μm particles was about 0.3 h⁻¹.

Finally, re-suspension emission rates in these offices were also calculated based on the assumption of spherical particles having unit density. The values were higher in the occupied and carpeted offices reflect human activities as the main cause for particle re-suspension. Re-suspension emission rates were as high as 235 μg m⁻³ h⁻¹ in the occupied offices and around 75 μg m⁻³ h⁻¹ in the unoccupied ones.

ACKNOWLEDGEMENT

This study was fully sponsored by the Deanship of Academic Research at the University of Jordan.

SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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Received for review, February 15, 2015
Revised, April 23, 2015
Accepted, May 22, 2015