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ARTICLE

Particle Size Distributions Inside a University Office in Amman, Jordan

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Abstract: We studied the number based particle size distribution (diameter 0.3–10 μm with high time-resolution) inside an office (naturally ventilated) at a university building in Jordan during two weeks (18.09.2013 – 01.10.2013). We analyzed and investigated the particle number and mass concentrations, their differences between workdays and weekends and the effect of tobacco smoke and worker activities inside the office. We also focused on three scenarios of office conditions: totally closed, totally open and open window. The 24-hour means of the $PM_{10\text{-}0.3}$ were 16.4–43.2 μg/m^3 on workdays and 4.4–8.5 μg/m^3 on weekends. The concentrations ranged from 4.3 μg/m^3 to 7.7 μg/m^3 (30.0–42.1 cm^{-3}) when the office was kept closed at nighttime and weekends. They also ranged from 5.2 μg/m^3 to 25.8 μg/m^3 (50.0–83.2 cm^{-3}) when the window was open at night. The highest concentration ranged from 2.5 μg/m^3 to 261.9 μg/m^3 (15.5–906.4 cm^{-3}) during the daytime on workdays when the office was open. The variation of aerosol concentrations is believed to be caused by increased urban activities on daytime and workdays, enhanced ventilation rate and penetration factor when the office was open, and the resuspension of carpet-dust by the office occupants and visitors. Smoking inside the office increased the aerosol concentration to 3729.2 μg/m^3 (4854.5 cm^{-3}) and the tobacco smoke remained sensible inside the office for more than 40 minutes. Since the mass concentrations presented here were calculated by assuming spherical particles and unit density and the measured size-range was larger than 300 nm in diameter, the PM_{10} is expected to be at least double the numbers shown in this study, and thus the 24-hour PM_{10} in the office would exceed the maximum value recommended by the WHO guidelines, which is not to exceed 50 μg/m^3 for more than 35 days per year.

Keywords: Indoor air quality; Particulate matter; Re-suspension; Natural ventilation; University building.

Introduction

According to activity diary studies, offices and workplaces are the second indoor environments where people spend most of their time [1]. Therefore, work places ought to be comfortable, because workers' performance and health are affected by thermal discomfort and poor air quality inside their offices [2]. For example, a worker's task performance decreases when he feels hot. Feeling hot at office might increase the worker's heart rate, respiratory ventilation and end-tidal partial pressure of carbon dioxide; and on the other hand, his/her arterial oxygen saturation decreases [2]. Besides environmental factors, symptoms in office workers can be also associated with psychosocial stress or even poor psychosocial conditions [3–4].

Beside the outdoor air as the main source of aerosol particles inside offices, these are produced during operation of office appliances

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such as printers [5–6]. Re-suspension can be also a significant source when occupants move intensively [7–10]. Smoking is another potential source of indoor aerosols when individuals violate smoking prohibition inside offices and public buildings. Slezakova et al. [11] confirmed that tobacco smoking significantly influences the composition of fine particles, and the particulate mass concentrations of five carcinogenic elements (Cr, Ni, As, Cd and Pb) were increased by one to three orders of magnitude. They also reported that S, K and Zn were predominantly present in the fine fraction and associated with tobacco smoking.

Recently, the Indoor Air Quality (IAQ) at workplace has been given increased attention. For instance, Fisk et al. [12] found out a large rate of submicron particles removal and a significant source/resuspension of micron particles inside mechanically ventilated office. Zuraimi and Tham [13] quantified the efficiency of dry-media and electrostatic precipitation filters used in mechanically ventilated offices; they reported that electrostatic precipitation filters are superior to media filters in removing fine particles with aerodynamic diameters >300 nm. Smolík et al. [14] evaluated fine and coarse particle deposition inside a naturally ventilated office. Among the main electrical machines used in offices, printers and photocopiers generate fine particles with high amounts that exceed several orders of magnitude what can be found in normal conditions [4–5, 15–16]. Hussein et al. [17–19] analyzed and modeled the fine particle number concentrations and size distributions inside mechanically ventilated offices; they showed that during the absence of indoor sources the indoor-to-outdoor relationship of fine aerosol particles is affected by three main parameters: ventilation, deposition and penetration. Quang et al. [20] also reported that $PM_{2.5}$ and number concentrations of particles smaller than 3 μm in diameter inside three mechanically ventilated urban offices are mainly from outdoor origin and that the ventilation and penetration are main factors controlling their transport from the outdoor air into the indoor air.

Industrially synthesized nanoparticles hold a big risk on workers [21–22], and therefore, Koivisto et al. [23] presented a concept to estimate the inhaled dose of industrially synthesized nanoparticles at workplace. Zitnik et al. [24] quantified the elemental composition of PM_{10} at a medium-sized mechanical workshop and a chemistry laboratory dealing with processing advanced nano-particulate materials; they recommended an hourly time-resolution to be used for elemental analysis because 24-hours is too coarse and high-time resolution contains large variability.

With respect to educational buildings and exposure of teachers and students, Buonanno et al. [8] and Branis and Safranek [9] showed that the dominant source of the coarse fraction inside school gyms is particle re-suspension due to exercising activities by pupils. Gaidajis and Angelakoglou [25] showed that PM_{10} and $PM_{2.5}$ concentrations were significantly higher in the open access meeting place of common use as a result of student trespassing and occasional smoking. Salma et al. [26] identified two classes of coarse particles inside university buildings: general indoor dust particles with a residence time ~35 min and chalk particles with a residence time more than 20 min. Tran et al. [27] reported that elemental analysis of PM_{10} in French classrooms is increased during children's activities, but the elemental distribution was unaltered.

However, the number of investigations regarding the indoor air quality (IAQ) at work place is still very small when compared to other indoor environments such as houses and apartments. Also, the focus of previous studies has been very sparse. Beside that, measurements of particle size distributions inside offices are very few and need more attention. Furthermore, measurements of aerosols and their size distributions have never been reported in Jordan. In this study, we aim at investigating the particle size distributions inside a naturally ventilated office in a university campus in Jordan. We measured particle number size distributions (diameter between 0.3–10 μm and 1 minute time-resolution) during two weeks in autumn 2013. We analyzed the particle number and mass concentration differences between workdays and weekends and the effect of tobacco smoke and worker activities inside the office. We also focused on three scenarios of office conditions: totally closed, totally open and open window. We utilized a simple indoor aerosol model to estimate the ventilation rate of the office. According to our knowledge, this is the first study of its own to be presented for the scientific community.

Materials and Methods

Measurement Location

The measurement campaign was performed during the autumn (18.09. – 01.10.2013) inside an office in the building of the Faculty of Science at the University of Jordan, Amman. The dimensions of the office are 3m×6m×3m. The whole building was naturally ventilated via the main gate and windows. The office was furnished with a desk, a working chair, a PC table, four chairs, a middle and two side coffee tables, a folder metal-cabin, a safe, shelves, window curtains and a carpet which covered the whole floor. The office was located on the south-western corner of the building. The southern and western walls of the office contained large windows to allow air exchange with the ambient air.

The building itself was a two storey construction situated at the middle of the university campus, which is located in a suburban area at about 15 km north-west the city center. The surrounding is a residential area mixed with an urban forest and main streets. The main entrance was in the middle of the first storey facing the west and leads to the stairs way that divided the building into two unequal halves.

Aerosol Measurements and Data Handling

We measured the number size distributions of particles between 300 nm and 10 µm in diameter with an Optical Particle Sizer (OPS 3330, TSI). The instrument was calibrated by the manufacturer two months prior to the start of the measurement campaign. The OPS measurement is based on the optical diameter of the aerosol particle. The instrument also records the ambient temperature and pressure. We setup the OPS to operate in “TSI default” mode and the dead-time correction was performed throughout the measurement campaign. The sampling was carried out directly without using additional tubing at a height of about 1.3 m from the ground. Sampling time-resolution was set to 1 minute and sampling flow rate was 1 L/min.

The particle number size distributions were routinely checked for quality assurance. 100% of the measured data was valid and processed further to be prepared for data analysis. We calculated the 5-minute average and illustrated the data with 30-minute average. We also calculated average concentrations during longer time periods such as daytime or nighttime.

In order to attain an indication of the PM concentration level inside the office, we generated the number size distributions into mass size distributions by assuming spherical particles with unit density.

Office Occupancy and Scenarios

The office was occupied by the worker during the working hours between 08:00 and 17:00. It was very seldom when there were visitors or students in the office. During working hours, the main door of the building as well as the office window and door were all opened. Although the main door and all offices in the building were totally closed outside the working hours, we believe that the building was leaking air across the window shells. In order to investigate a different condition, we left the office’s window opened during the last three days of the measurement campaign; i.e. after 29.09.2013 for which we shall refer to as Period II and we shall denote Period I for the time period before that.

Even though smoking was not allowed inside the building, workers/visitors often smoked in other offices in the same floor. We also wanted to test the effect of smoking inside the office by performing a smoking event (three cigarettes during 10 minutes) by two persons on 26.09.2013. Another smoking event was performed with a single cigarette by a visitor on 19.09.2013.

Ventilation Rate Quantification

According to a previous model investigation for the indoor air by Molgaard et al. [28], it was evident that the ventilation rate can be quantified by considering the variation in the number concentration of aerosol particles within the diameter range 0.1–1.0 µm emitted indoors and causing significantly high concentrations. This condition was valid during the smoking event on 26.09.2013, when the building and the office were opened. It was also possible to estimate the ventilation rate when the office was totally closed on 24.09.2013 right after leaving the office.

The approach of the ventilation rate estimation was previously described in details elsewhere [29]. The principle is based on the fact that aerosol particles within the diameter range 0.1–1.0 µm have the lowest deposition velocity; and thus, they remain airborne for a long time.

Assuming that the indoor air is well mixed, the indoor particle concentration of a certain particle size follows the mass-balance equation:

$$\frac{d}{dt} I_i = P_i \lambda O_i - (\lambda + \lambda_{d,i}) I_i \tag{1}$$

where I_i and O_i [μg/m^3 or cm^{-3}] are the indoor and outdoor particle concentrations, respectively; P [--] is the penetration factor of aerosol particles into the office, λ [h^{-1}] is the ventilation rate and λ_d [h^{-1}] is the deposition rate of aerosol particles onto available indoor surfaces. According to the model application requirement, additional terms can be added to the right side of the equation to denote for the change rate due to other processes such as emissions, re-suspension, coagulation… etc. Here, the subscript i denotes that the equation is applied for a certain particle size-range having the same physical properties and dynamic behavior.

Assuming further that the outdoor particle concentration remains rather constant as well as the parameters P, λ and λ_d that define the indoor-to-outdoor relationship of aerosol particles, then a simple mathematical solution can be found for this mass-balance equation [30–31]:

$$I_i(t) = \frac{P_i \lambda O_i}{\lambda + \lambda_{d,i}} + \left[I_i(t_0) - \frac{P_i \lambda O_i}{\lambda + \lambda_{d,i}} \right] \cdot e^{-(\lambda + \lambda_{d,i})t} \tag{2}$$

where t [h] is time and $I_i(t_0)$ is the initial particle concentration at time t_0.

Generating a large amount of indoor aerosols (e.g. a smoking event) that increases their concentrations to values higher than those found outdoors can simplify this solution and allow for an estimation for the combined term ventilation rate and deposition rate:

$$\ln\left(\frac{I_i(t_0)}{I_i(t)} \right) = (\lambda + \lambda_{d,i})t \ . \tag{3}$$

Therefore, the ventilation rate (λ) can be calculated by using Eq. 3 as the best-fit line to the variation of the particle number concentration within the diameter range 0.1–1.0 μm, which has a small deposition rate compared to the ventilation rate (i.e. $\lambda_\delta << \lambda$), right after an indoor source that generated the high concentrations of indoor particles with the initial condition at t_0 assigned at a time after turning off the indoor source. We have to keep in mind that the time period used to fit Eq. 3 requires one more assumption stating that we can neglect the change rate due to coagulation and other processes [32].

Results and Discussion

Indoor Ambient Conditions and Office Ventilation

Air temperature inside the office varied between 33.5 and 41 Celsius degrees. It showed a clear daily pattern with maxima in the afternoon and minima in the morning (FIG. 1e). That was mainly because the office orientation with respect to the sun; it is located in the south-western corner of the building. The ambient pressure varied between 90.1 and 90.9 kPa and also showed a clear daily pattern with two peaks: one around noon and one around midnight.

According to Eq. 3, the ventilation rate estimation (λ) requires an indoor source of aerosol particles that produces significantly high concentrations within a certain time. Once the source is terminated, it is possible to follow the concentration decay of particles within the diameter range 0.1–1.0 μm. This condition was satisfied during and after the smoking event that occurred during the working hours on 26.09.2013. This yields an estimated ventilation rate ~2 h^{-1} during the open office conditions.

We also checked the measured data and the marked information in the log-book looking for other situations that are valid to apply Eq. 3. We figured out that on Tuesday 24.09.2013 around 16:00 there were several persons in the nearby office smoking heavily causing an increase in the concentrations inside the office, where the measurement was performed. After closing the office (around 16:30), the concentrations inside the office started to decay; and from this situation we estimated the ventilation rate λ ~0.5 h^{-1} for the closed office condition.

According to these estimates, the ventilation rate would vary between 0.5 and 2 h^{-1} with low ventilation during the closed office situations and high values during the open office situations. These values compare rather well with available estimates for natural ventilation inside offices and dwellings [30–31].

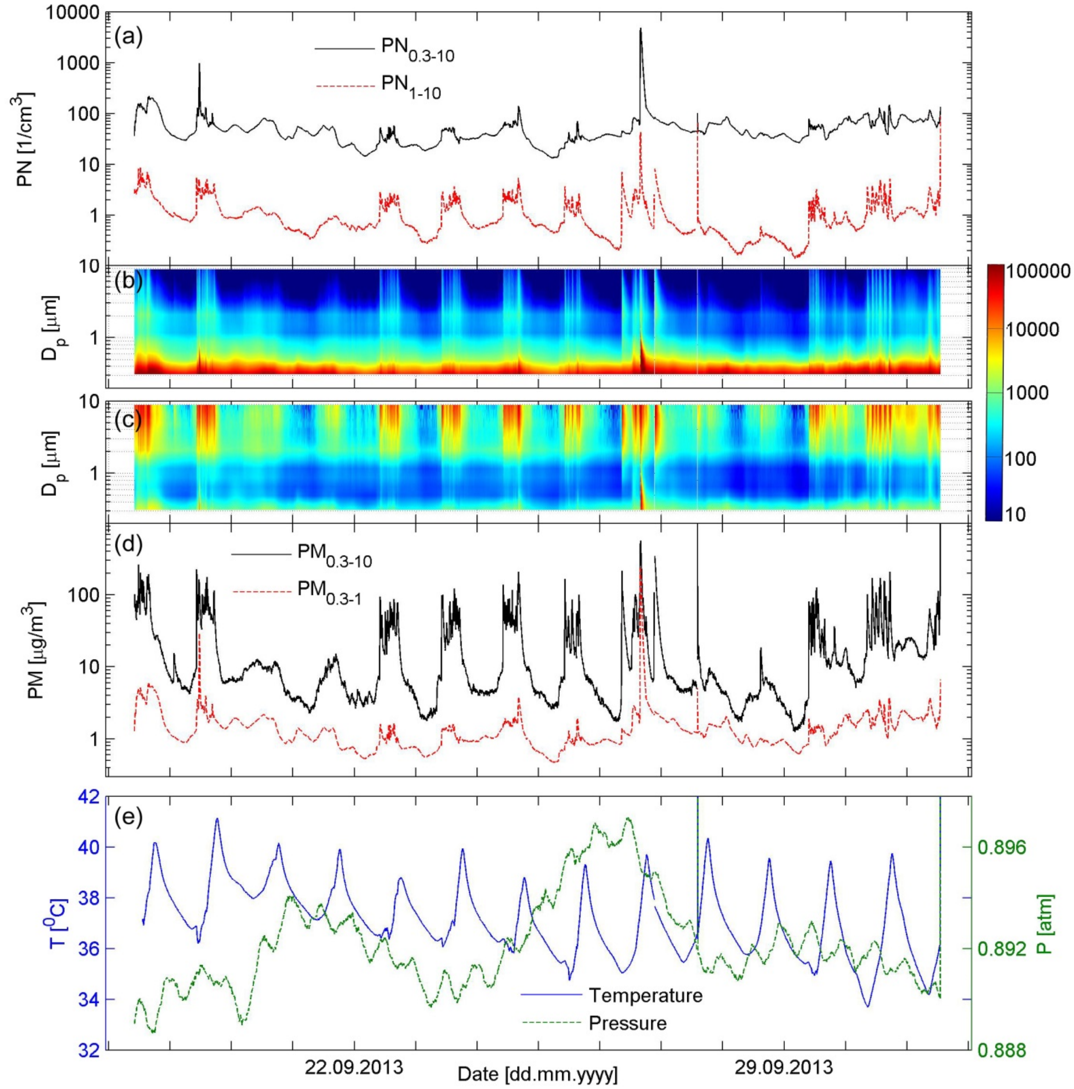

FIG. 1. Time series based on the 5-minute average: (a) integrated particle number concentrations, (b) particle number size distribution spectrum, (c) particle mass size distribution spectrum, (d) integrated particle mass concentrations and (e) indoor temperature and pressure

Average Concentrations and Size Distributions

The measured particle number size distributions and the calculated particle mass size distributions are presented in FIG. 1b and 1c, respectively. As mentioned in the methods section, we calculated the mass concentrations by assuming spherical particles and unit particle density. According to the measurement scenarios, the office (also the whole building) was open in the daytime (working hours) on workdays. The office was totally closed at night before 29.09.2013 and after that we left the window open overnight. These would be three different scenarios as: (1) totally closed office during weekends and nighttime, (2) open window at nighttime after 29.09.2013 and (3) open office during daytime on workdays. We considered daytime hours as 08:00 – 18:00, and nighttime hours starting from 22:00 and ending at 06:00 on the next morning.

During the weekends (totally closed office), the $PM_{10-0.3}$ inside the office was on average 5.7±2.9 $\mu g/m^3$ (37.0±13.3 cm^{-3}), and ranging between 1.3–15.2 $\mu g/m^3$ (12.1–74.3 cm^{-3}) with values higher than 2.5 $\mu g/m^3$ (20.9 cm^{-3}) recorded during the daytime (TABLE 1). The daytime values on weekends were on average

7.7±3.2 μg/m^3 (42.1±11.3 cm^{-3}), indicating that the concentrations of aerosol particles within the measured size range increase during the daytime due to urban activities (FIG. 1a and GIG.1d). The nighttime values inside the closed office were on average 4.3±1.9 μg/m^3 (30.0±12.7 cm^{-3}).

Obviously, the concentrations increased by opening the window and keeping the door closed (nighttime after 29.09.2013); in that case the nighttime values were on average 15.0±6.5 μg/m^3 (63.1±7.5 cm^{-3}) and ranging between 5.2–25.8 μg/m^3 (50.0 – 83.2 cm^{-3}). The highest concentrations were recorded during the daytime on workdays (open office); these ranged between 2.5–261.9 μg/m^3 (15.5–906.4 cm^{-3}) with an average value of 43.7±37.0 μg/m^3 (54.6±49.6 cm^{-3}). The high concentrations during the workdays' daytime period were mainly due to three reasons: First, the urban activities are expected to be more on workdays usually causing higher outdoor concentrations in the daytime than at night; second, both the ventilation rate and the penetration factor are enhanced during the daytime because the office was totally open; and third, the office was occupied by at least the worker himself, who can be considered as a cause of particle re-suspension from the carpet and other surfaces in the office as will be discussed in the next section. According to estimations, the ventilation rate (λ) was ~2 h^{-1} when the office was open and ~0.5 h^{-1} when the office was totally closed. In general, the higher the penetration factor is, the higher are the concentrations inside an office and an enhanced ventilation rate enhances the response in the change-rate of the indoor concentrations [29–33].

TABLE 1. Particulate mass and particulate number concentrations within the measured size-range

		$PM_{10\text{-}0.3}$ [μg/m^3]				$PN_{10\text{-}0.3}$ [1/cm^3]			
Office Condition	**Time Period**	**mean ± std.dev.**	**25%**	**median**	**75%**	**mean ± std.dev.**	**25%**	**median**	**75%**
Totally closed	Period I – Weekends$^{(a)}$	5.7 ± 2.9	3.5	4.7	7.4	37.0 ± 13.3	27.5	36.7	45.9
Totally closed	Period I – Weekends (Daytime) $^{(b)}$	7.7 ± 3.2	4.6	8.3	10.6	42.1 ± 11.3	33.8	40.3	47.6
Totally closed	Period I – Weekends and Workdays (Nighttime) $^{(c)}$	4.3 ± 1.9	3.0	3.9	4.8	30.0 ± 12.7	19.9	28.8	37.3
Open door or/and window	Periods I and II – Workdays (Daytime) $^{(b)}$	43.7 ± 37.0	17.4	34.2	58.4	54.6 ± 49.6	29.1	43.2	62.3
Open window	Period II – Workdays (nighttime) $^{(c)}$	15.0 ± 6.5	9.0	14.7	20.6	63.1 ± 7.5	58.5	62.2	66.1

$^{(a)}$ This includes either weekends or workdays as specified by considering the time period 00:00 – 24:00.

$^{(b)}$ Daytime period was defined between 08:00 and 18:00.

$^{(c)}$ Nighttime period was defined before 06:00 or after 22:00.

Based on the particle number, the coarse fraction was uni-modal (FIG. 2a). The average particle mass size distributions showed that the coarse mode extends beyond 10 μm in diameter (FIG. 2b). The average concentration of the coarse fraction was 6.4±3.0 cm^{-3} μg/m^3 (0.7±0.4 cm^{-3}) during daytime on weekends and 3.3±1.7 μg/m^3 (0.5±0.3 cm^{-3}) during nighttime; during these two cases, the office was totally closed. The average concentrations were 41.4±35.7 μg/m^3 (1.9±1.2 cm^{-3}) when the office was open during the daytime on workdays. When the window was open, they were about 13.0±6.3 μg/m^3 (1.0±0.3 cm^{-3}). Hussein et al. [34] previously measured the total particle number concentrations (D_p > 10 nm) at the same location; they reported the 5-minute average to vary from 10^4 cm^{-3} in the nighttime to a value as high as 10^5 cm^{-3} in the daytime. This indicates that the majority of the aerosol particles are in the fine particle size-range.

Keeping in mind that we generated the mass concentrations by assuming spherical particles and unit density, the mass concentration of the coarse fraction is expected to be at least doubled. Furthermore, the measured particle size diameter was larger than 300 nm, and that suggests higher values for the PM_{10}. It is, however, difficult to make a reasonable guess for the PM_{10} here, because we do not have enough information about the size distribution of the fine fraction. Based on these two facts, the 24-hour values reported (TABLE 2) here for this office easily exceed what is recommended by the WHO guidelines as 50 μg/m^3 for PM_{10} and 25 μg/m^3 for $PM_{2.5}$. The reported numbers are also higher than those found in the literature regarding university buildings. For example, Salma et al. [26] measured the PM_{10} concentrations in a lecture hall at a university in Hungary during a week. The day-to-day variation showed a rather similar trend as that observed here in this study reflecting the high concentrations on workdays' daytime and low concentration at nighttime and weekends. Their reported values for the PM_{10} were as high as 100 μg/m^3 with a median value of 15.3 μg/m^3. Gaidajis and Angelakoglou [25] showed that the 24-hour concentrations of PM_{10} and $PM_{2.5}$ 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. This indicates that the coarse fraction would be in the range 14–102 μg/m^3. Tran et al. [27] reported PM_{10} concentrations in French classrooms: The weekly averages of occupied classrooms ranged between 72.7 – 85.3 μg/m^3 and those of unoccupied classrooms ranged between 13.2 – 24.8 μg/m^3. The corresponding outdoor values were 29.6 – 51 μg/m^3 and 23.1 – 29.3 μg/m^3, respectively.

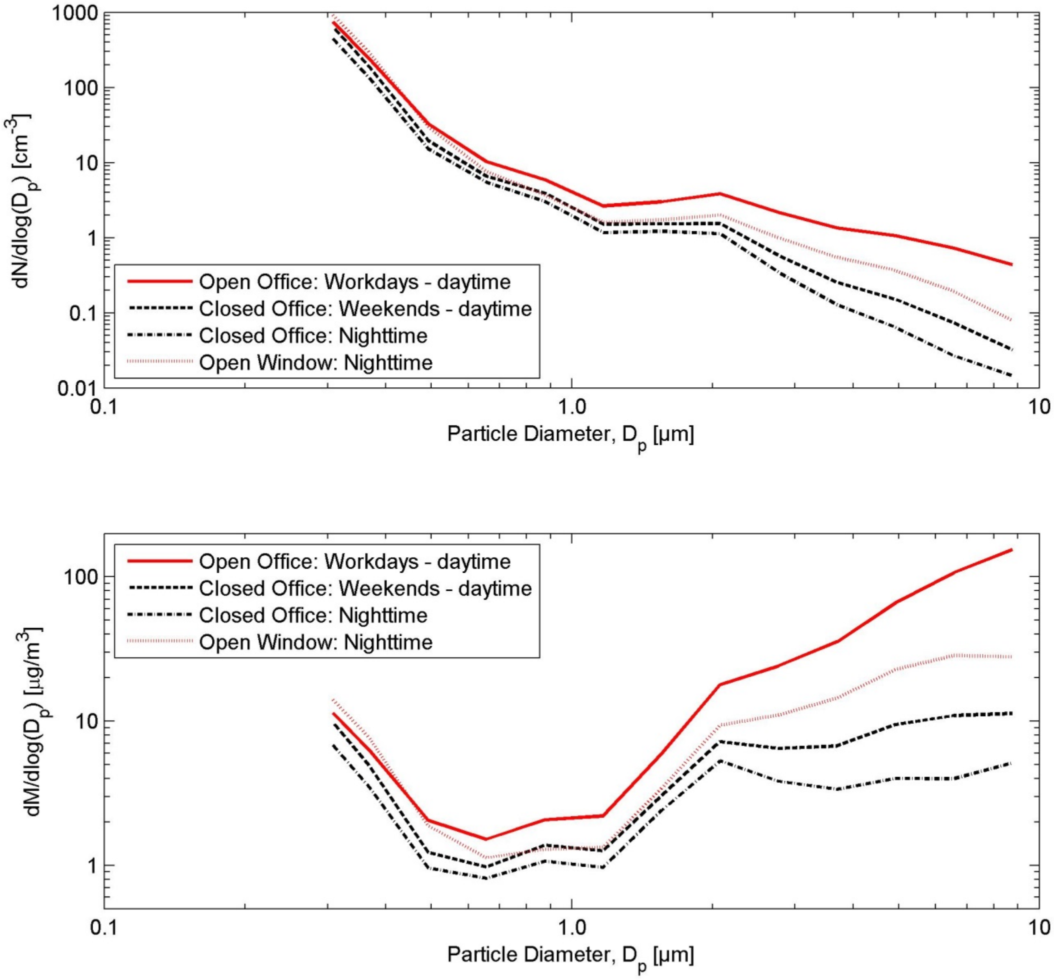

FIG. 2. (a) Average particle number size distributions and (b) the corresponding particle mass size distribution

TABLE 2. Daily averages of the particle mass [$\mu g/m^3$] and particle number concentrations [cm^{-3}] within different measured size-fractions

Date	$PM_{10-0.3}$	$PM_{1-0.3}$	PM_{10-1}	$PN_{10-0.3}$	$PN_{1-0.3}$	PN_{10-1}
19.09.2013	28.7	1.8	27.6	60.0	58.5	1.6
20.09.2013	8.5	1.6	7.0	52.4	51.4	1.0
21.09.2013	6.1	1.1	5.1	39.6	39.0	0.6
22.09.2013	16.4	0.8	16.0	24.9	24.0	1.0
23.09.2013	18.7	0.9	18.3	30.9	30.0	0.9
24.09.2013	24.1	1.3	23.4	45.1	43.9	1.2
25.09.2013	14.0	0.8	13.5	25.5	24.7	0.8
26.09.2013	43.2	6.6	37.3	181.8	180.1	1.9
27.09.2013	6.9	1.5	5.5	54.5	54.0	0.6
28.09.2013	4.4	1.1	3.4	44.0	43.7	0.3
29.09.2013	18.2	1.1	17.6	44.0	43.3	0.7
30.09.2013	29.6	2.0	28.1	75.6	74.3	1.3

Concentrations during Office Activities: Tobacco Smoke and Re-suspension

So far, we have not considered the unusual activities (such as smoking or more than two visitors/students) in the office. The concentrations were as high as 3729.2 $\mu g/m^3$ (4854.5 cm^{-3}) during the smoking event on Thursday 29.09.2013 (FIG. 1a and FIG. 1d). Another smoking event occurred in the nearby office on Tuesday 24.09.2013; that caused the concentrations to reach as high as 235 $\mu g/m^3$ (150 cm^{-3}). The coarse particle size fraction did not show any change due to these smoking events and the increase in the concentrations was mainly observed in the particles smaller than 1 μm in diameter (FIG. 3). It is very well noticed that the tobacco smoke remained in the office for longer than 40 minutes.

Afshari et al. [35] considered cigarette smoking during 10 minutes and showed that the fine particle number concentration and also particles larger than 1 μm suddenly increased to more than 10^5 cm^{-3} and stayed airborne for more than 100 minutes. Hussein et al. [31] reported that smoking a cigarette in a living room increased the fine particle number concentrations from the background level (6×10^3 cm^{-3}) to about 3.6×10^4 cm^{-3} with a well-distinguished fine mode extending up to 600 nm. He et al. [36] also measured the fine particle number concentrations of tobacco smoke to be 2.7×10^4 cm^{-3}, which was about 1.5 the background level. Morawska et al. [37] reported even concentrations as high as 3.5×10^6 cm^{-3} during tobacco smoking.

The concentrations during the daytime on workdays were significantly higher than those observed during the same time period on weekends. Entering the office when it was totally closed caused the concentrations of coarse particles to increase suddenly. For example, the routine check-up visit on Saturday 28.09.2013 (around 14:00) increased the PM_{10-1} from 5 $\mu g/m^3$ to about 20 $\mu g/m^3$ (PN_{10-1} from 0.3 cm^{-3} to about 1 cm^{-3}) (FIG. 1a and FIG. 1d). The size fraction below 1 μm did not show changes in concentration (FIG. 4). This is a strong indication of the re-suspension process by walking over the carpet and also probably disturbing the dust layer accumulated on other surfaces.

At school gyms, Branis and Safranek [9] reported that the indoor-to-outdoor (I/O) ratio of the coarse particle fraction on workdays was higher than two, where the indoor $PM_{10-2.5}$ varied between 1.2–29.4 $\mu g/m^3$. During weekends and holidays, the I/O ratio was below 0.5 with the indoor $PM_{10-2.5}$ varied between 0.5–4.9 $\mu g/m^3$. According to Branis and Safranek [9], the differences were explained by sport activities in the gyms that enhance re-suspension of particulate matter. In another study about school gyms, Buonanno et al. [8] confirmed that the I/O ratio of the $PM_{10-2.5}$ was 4.8±2.0 with the dominant indoor source being the particle re-suspension due to exercising activities of pupils. Buonanno et al. [8] estimated the $PM_{10-2.5}$ emission factors in the range of 1.5–8.9 mg/min. These re-suspension rates were slightly higher than those presented by Ferro et al. [7] as 0.03–0.5 mg/min for $PM_{2.5}$ and 0.1–1.4 mg/min for PM_5. The differences between Buonanno et al. [8] and Ferro et al. [7] are possibly due to the difference in the considered particle size range.

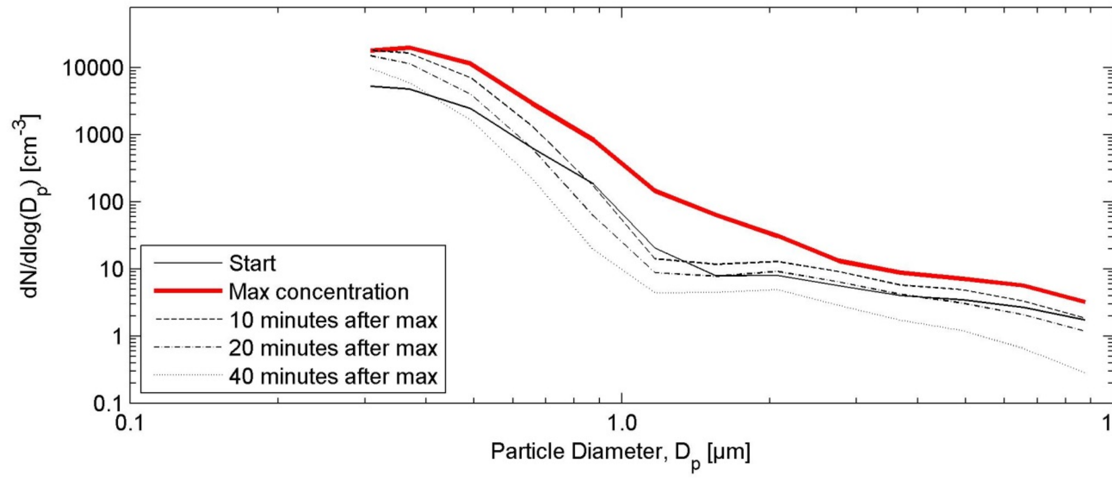

FIG. 3. Evolution of the particle number size distribution during the smoking event on Thursday 26.09.2013. The office was open

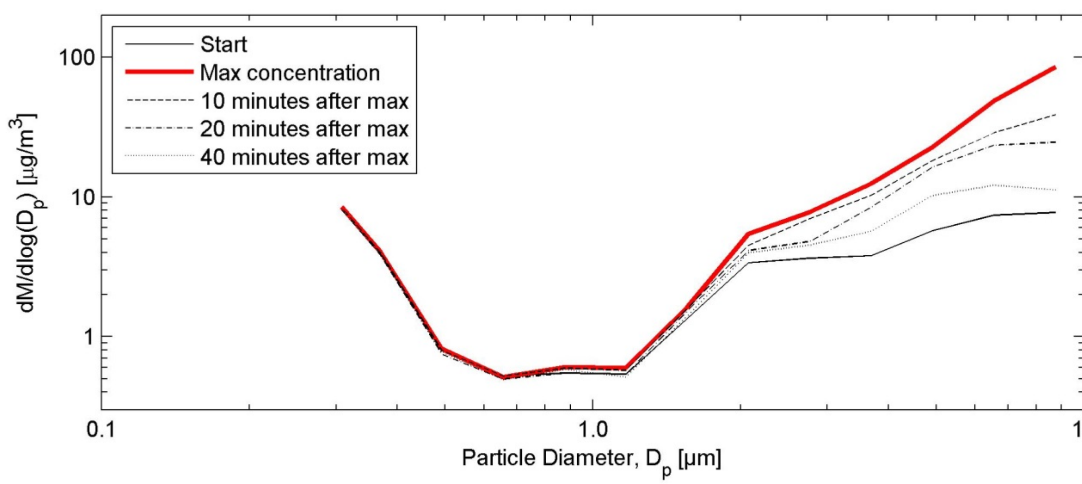

FIG. 4. Evolution of the particle mass size distribution as an example of particle re-suspension due to walking into the office on Saturday 28.09.2013. The office was totally closed

Conclusions

We measured the particle number size distribution (diameter 0.3–10 µm and one minute time-resolution) inside a naturally ventilated office located at a university building in Jordan. The measurement campaign covered a time period of two weeks (18.09.2013 – 01.10.2013) with 100% valid data. We focused on the variation of the particle number and particle mass (assuming spherical particles with unit density) concentrations, their differences between workdays and weekends and the effect of special activities inside the office (tobacco smoking and re-suspension). We also focused on three scenarios of office conditions: totally closed, totally open and open window. The ventilation rate was estimated by utilizing a simple indoor aerosol model.

The 24-hour means of the $PM_{10\text{-}0.3}$ ranged between 16.4–43.2 µg/m^3 and 4.4 – 8.5 µg/m^3 on workdays and weekends, respectively. They ranged between 7.7±3.2 µg/m^3 (42.1±11.3 cm^{-3}) and 4.3±1.9 µg/m^3 (30.0±12.7 cm^{-3}) when the office was totally closed at daytime (weekends) and nighttime, respectively. The $PM_{10\text{–}0.3}$ ranged between 5.2–25.8 µg/m^3 (50.0 – 83.2 cm^{-3}) when the window was open at night. The highest concentrations were observed during the daytime on workdays (open office); these ranged between 2.5–261.9 µg/m^3 (15.5–906.4 cm^{-3}). The differences in the closed office conditions between daytime and nighttime are simply explained by higher concentrations outdoors during the time reflecting the increased urban activities in the city. Opening the window caused an increase in the concentrations as a result of enhanced ventilation rate and penetration factor. The highest concentrations on workdays daytime are believed to be the result of several factors: (1) increased urban activities on workdays' daytime, (2) enhanced ventilation rate and penetration factor, because the office was open and (3) the office was occupied by at least the worker himself who can be considered as a cause of particle re-suspension from the carpet and other surfaces. The concentrations were as high as 3729.2 $\mu g/m^3$ (4854.5 cm^{-3}) during the smoking events inside the office, where the tobacco smoke effect remained for more than 40 minutes.

The particle number size distribution of the coarse fraction was uni-modal, whereas the particle mass size distributions showed that the uni-mode extends beyond 10 μm in diameter. The average concentration of the coarse fraction was about 3.3±1.7 $\mu g/m^3$ (0.5±0.3 cm^{-3}) during nighttime, whereas during workdays' daytime it was 41.4±35.7 $\mu g/m^3$ (1.9±1.2 cm^{-3}).

It should be emphasized that the mass concentrations presented here were calculated by assuming spherical particles and unit density and the measured size-range was larger than 300 nm in diameter. Therefore, the PM_{10} is expected to be at least double the numbers shown in this study, which implies that the 24-hour PM_{10} in this office likely exceeds what is recommended by the WHO guidelines.

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