Aerosol Particles (0.3–10 µm) inside a Workshop Area–Emission Rate and Deposited Dose

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Abstract

The main objective of this study was to investigate the accumulation and coarse particles concentration inside an educational workshop and calculate emissions factors as well inhaled deposited dose. We measured the particle number distribution (diameter 0.3–10 µm) and focused on two particle size fractions: submicron particles in the diameter range 0.3–1 µm and coarse particles (1–10 µm). The occupants activities inside the workshop included coffee brewing, lecturing, tobacco smoking, welding, scrubbing, and sorting/drilling iron. The highest concentrations were observed during welding activities; mean $PN_{0.3–1}$ ($PM_{0.3–1}$) and $PN_{1–10}$ ($PM_{1–10}$) concentrations were about 1865.86 (54.49 µg/m^3) and 6.46 cm^{-3} (102.54 µg/m^3) with most of the particles were emitted below 1 µm in diameter. The alveolar received the majority and particles below 1 µm with a fraction of about 53% of the total inhaled deposited dose whereas the head/throat region received about 18%.

Keywords: Particulate matter; Indoor air quality; Emission rate; Deposited dose; Educational workshop

1. Introduction

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The indoor air tends to be contaminated by more pollutants than the air outdoors [1–4]. Some indoor pollutant concentrations have been reported to be 2–5 times higher and in some occasions even more than 100 times higher than those outdoors [5].

Particles originate from either outdoor or indoor sources or a combination of both [3,13]. Human activity such as tobacco smoking, walking, cooking, vacuuming, cleaning, using kerosene for heating and burning wood for heating or cooking are the main sources of indoor pollutants [14–15]. Moreover, re-suspension by indoor activities (i.e. active walking, cleaning, and dusting) and combustion processes such as toasting, oven roasting or baking, barbecuing are major sources of particles larger than 2.5 μm and fine particles, respectively. [14, 16–17, 22–24]. Furthermore, He [23] reported that fine mode of particles in indoor environments was also generated by sources such as biological pollutants and sprays. Elevated concentrations of $PM_{2.5}$ and PM_1 were also observed during cooking and tobacco smoking [21].. Particles of various sizes produced by outdoor sources, can be introduced into indoor environments through infiltration processes that are linked to ventilation systems, building features and materials [3,9,13].

Indoor Air Quality (IAQ) in educational facilities is associated with ventilation mechanisms, furniture, high occupant density, type of activities and the re-suspension of particles from disturbances caused by the dynamic motion of occupiers [3, 28–30]. The performance of students and teachers, their health and well-being depend on good indoor air quality [1, 31–35].

Regarding the relationship between IAQ and workplaces such as offices, studies reported that great quantities of particles are emitted by office electronic equipment such as copiers, printers and computers [6, 36–40]. Moreover, IAQ has been associated with the efficiency of employees and health effects caused by psychosocial and environmental conditions that occurred in the work environment [13, 41–43]. Hedge et al. [44], Hodgson and Collopy [45] and Gyntelberg et al. [46] assessed airborne particulate matter and dust in non-industrial buildings and confirmed that health related issues and poor performance of workers are closely related to bad air quality. Moreover,

several studies documented eye, nose and throat irritation symptoms that were caused by coming into contact with office dust [45, 47–48].

Special attention has been paid lately to particulate matter emitted from manufacturing processes in industrial environments. For example, Chan et al. [49], Thornburg and Leith [50] and Iavicoli et al. [51] pointed out that the majority of the processes taking place in a metallurgic industry generated particles larger than 1 μm in diameter, whereas other procedures were considered to be major sources of sub-micrometer particles, too. Moreover, operations in industrial workplaces that include welding, grinding, smelting, soldering, laser ablation, cutting, polishing, and heat treating are considered to be significant sources of ultra-fine particles [51–56]. Riediger and Möhlmann[59] reported that particle number concentrations of ultra-fine particles produced by activities such as plasma cutting, metal grinding, brazing, smelting, laser ablation, and metal inert gas and tungsten inert gas welding ranged from 2.0×10^4 to 4.0×10^7 particles cm^{-3}. Occupational exposure to gases and particulate matter originating from welding fumes is strongly correlated to adverse health implications such as asthma, chronic bronchitis, respiratory problems, metal fume fever, pneumoconiosis and increased probability of lung cancer [55, 60–64].

Knowledge on occupational exposure to coarse particles inside workshops is currently very limited [51–56]. Moreover, most of the research has focused on measuring and reporting the particle mass and number concentration of the coarse and fine particles, respectively [51,56, 65–69]. The emission factors as well as the inhaled deposited dose in the respiratory system were seldom mentioned in previous research. Therefore, the main objective of this study therefore was to assess the exposure to large particles inside an educational workshop. We measured the particle number size distribution (0.3–10 μm) during March 31st until April 6th 2015. We focused on investigating the effects of some indoor activities (such as lecturing, smoking, coffee brewing, iron welding, turning and sorting/drilling) on the particle concentrations. In addition, a simple indoor aerosol model was

used in order to estimate the loss rate and the emission rate of aerosol particles inside the workshop area. The inhaled deposited dose was also calculated for the time period of indoor activities.

2. Materials and Methods

2.1. Measurement location

The measurement campaign (March 31 – April 6, 2015) took place inside an educational workshop at the Department of Physics, University of Jordan. The Department of Physics is a three-floor construction (naturally ventilated) located at the middle of the campus. The workshop itself (32 × 10 × 3 m^3) was located on the ground floor. It consisted of student training workshop, office, storage room, changing room, wood workshop room, metal workshop room (equipped with welding machinery), and a main workshop area (equipped with turnery/metal-work machinery) (Fig. 1). The workshop was occupied during 8:00–16:00 by workers and/or visitors on workdays. Sometimes, it was occupied by students training. The majority of the windows were kept open during working hours.

2.2. Aerosol Measurements

The particle number size distribution (0.3–10 μm) was measured with an Optical Particle Sizer (TSI OPS 3330, 13 size-bins, 1 minute time resolution, 1 L/min flow rate, and dead-time correction). The instrument was calibrated by the manufacturer and it was located in the metal and welding section of the workshop (Fig. 1). The distance between the OPS and the windows was 2.5 m. The sampling was performed directly without additional tubing at a height of about 1.6 m above the ground, which represented the breathing zone above the ground.

2.3. Data Handling

The aerosol data were first quality checked and validated. We calculated the size-fractionated particle number (PN) concentration and calculated mean, maxima, minima and median values at different percentiles (5%, 25%, 75% and 90%) for different events (Tables 1 and 2). Particle mass concentration (PM) was also calculated (Tables 3 and 4).

2.4. Indoor aerosol modeling

The dynamic behavior of indoor aerosols can be described by the mass-balance equation [70–71]:

$$\frac{dI}{dt} = \lambda PO - (\lambda + \lambda_d)I + ER \quad (1)$$

where I and O are the aerosol particle concentrations indoors and outdoors, respectively, P is the penetration factor of aerosol particles across the building shell (natural ventilation) or a standard filter installed in a mechanical ventilation system, λ is the ventilation rate, λ_d is the deposition rate of aerosol particle onto available indoor surfaces, and ER is the emission rate of aerosol particles indoors. This mass-balance equation describes a certain particle size-fraction where aerosol particles have rather similar physical properties.

Although this mass-balance equation is primarily used to simulate and predict the indoor aerosol particles and their behavior, it can be used in inverse modeling to estimate some parameters such as P, λ, λ_d or even ER [72–73]. It was utilized it in the current study to calculate the loss rate of aerosol particles, according to the principles described by Hussein [43] and Hussein et al. [13]. Subsequently, the emission rates were estimated according to the semi-empirical approach described by Hussein et al. [73].

In general, the particle losses ($\lambda+\lambda_d$,) include indoor-outdoor air exchange, which was natural ventilation in this case, and dry deposition onto indoor surfaces. Hussein [43] and Hussein et al. [13] emphasized that particle losses can be estimated by analyzing occasions where large amounts of

indoor aerosol particles are produced during indoor activities. Such cases cause higher indoor aerosol concentrations compared to outdoor concentrations. When the indoor sources are stopped, the decline of indoor aerosol concentrations is observed.

2.5. Exposure and deposited dose estimation

The inhaled deposited dose inside the respiratory system was evaluated according to Hussein et al. [73–74]:

$$Deposited\ dose_{PM} = \int_{t1}^{t2} \int_{D_{p1}}^{D_{p2}} V_E \cdot DF \cdot n_N^0 \cdot f \cdot dlogD_p \cdot dt \quad (2)$$

where V_E ([L/min^1] or [m^3/h^1]) is the minute ventilation (known also as volume of air breathed per time), DF [--] is the respiratory deposition fraction of aerosol particles and $n_N^0 = \frac{dN}{dlog(D_p)}$ [particles cm^{-3}], where D_p is the particle diameter, is the lognormal particle number distribution. It should be noted that both DF and n_N^0 are functions of log(D_p). f is a dose metric such as the particle surface area (πD_p^2) or particle mass ($\frac{\pi}{6} D_p^3 \rho_p$). In our case f is the particle mass. The integrals are evaluated during an exposure time period $\Delta t = t_2$-t_1 to large particles (1–10 μm) on any time resolution.

The volume air breathed per time (i.e. the minute ventilation), V_E, is strongly associated with the body size [75], the activity, the age and the breathing frequency of the substance [76–77]. Values for the volume air breathed per time used in this study were adopted from Holmes [76] and Hussein et al. [74].

The respiratory deposition fraction, DF, is defined as the probability of aerosol particles to deposit in the respiratory system and it strongly depends on the gender and the activity level of the subject [78]. Moreover, the same group reported that the size range and the hygroscopicity of aerosol particles affect the DF. In particular, they pointed out the smaller the particle is the higher the DF is expected to be. Due to the fact that the relative humidity in the respiratory system and, more specifically, in the lungs is approximately 99.5% [79–80], the diffusion rate and the DF of

hygroscopic particles decrease [78]. Moreover, since the respiratory system consists of the head/throat, tracheobronchial and the pulmonary/alveolar region, the respiratory deposition fraction varies accordingly [77–78]. For our calculations, the respiratory deposition fraction values were taken from the GMD (deposition) curve of large particles (1–10 μm) as presented by Hussein et al. [73].

2.6. Scenarios of workers' activities

The workshop was occupied from 08:00 until 16:00 during the workdays only. The indoor activities included:

1) iron welding and smoking,

2) (exhaust) fan and welding machine on, iron welding without the fan running,

3) (exhaust) fan on, iron welding (with exhaust fan) and sorting/drilling,

4) making coffee and metal turning,

5) metal turning and iron welding,

6) metal turning,

7) lecture and metal turning, and

8) three undefined events.

A more detailed description about these events is given in Table S1. During these events, 1–4 people occupied one or more sections (1, 2, 4, 5, and 6 sections see Fig. 1) of the workshop. In spite of that, the number of people in section 3 (i.e. students training section) was as many as 10 persons during practical training class (Fig. 1).

3. RESULTS AND DISCUSSION

3.1. Mean concentrations

During the weekend, when the workshop was unoccupied, the $PN_{0.3–10}$ varied from 12.86–64.64 cm^{-3} whereas $PM_{0.3–10}$ ranged between 1.68–13.58 $\mu g/m^3$ (Figs. 2 and Fig. 3). In general, total $PN_{0.3–10}$ and $PN_{1–10}$ were increased during the occupants activities. During workdays, the $PN_{0.3–10}$ varied between 23.13 and 4162.44 cm^{-3} (Fig. 2) and the corresponding calculated $PM_{0.3–10}$ varied between 1.15 to 596.60 $\mu g/m^3$.

The highest mean and median particle number and mass concentrations of both submicron (0.3–1 μm) and micron (1–10 μm) particles were observed during the operation of the welding machine followed by the activity of iron welding without the use of the exhaust fan and the running of the exhaust fan afterwards (Event 2). In particular, mean and median $PN_{0.3–1}$ ($PM_{0.3–1}$) were about 1865.86 and 1958.63 cm^{-3} (54.49 and 54.80 $\mu g/m^3$), respectively, and mean and median $PN_{1–10}$ ($PM_{1–10}$) concentrations were 6.46 and 5.80 cm^{-3} (102.54 and 94.15 $\mu g/m^3$), respectively (Tables 1–4). This observation was during the consumption of 1 coated rutile electrode (E 6013) in combination with one tobacco smoking event that occurred inside the changing room of the workshop area (Figs. 2 and 3).

During Event 3 ((Exhaust) fan on, iron welding (with exhaust fan) & sorting/drilling), the $PN_{1–10}$ ($PM_{1–10}$) and $PN_{0.3–1}$ ($PM_{0.3–1}$) values were as high as 25.36 cm^{-3} (456.28 $\mu g/m^3$) and 4140.17 cm^{-3} (152.07 $\mu g/m^3$). During this event 2 coated rutile electrodes (E 6013) were used in the iron welding (Tables 2–5). The rutile electrodes were used only during Events 2 and 3, and therefore, it was assumed that their consumption might have been the reason for these high concentrations mentioned above.

It was also observed that while one person was welding iron in the metal and welding section of the workshop and another was smoking a cigarette inside the office of the workshop area (Event 1), $PN_{0.3–1}$ and $PN_{1–10}$ concentrations also exhibited high mean and maxima values (similar to Events 2 and 3) (Tables 1-4). More specifically, mean $PN_{0.3–1}$ ($PM_{0.3–1}$) and $PN_{1–10}$ ($PM_{1–10}$) concentrations

were equal to 885.67 cm^{-3} (24.95 $\mu g/m^3$) and 4.46 cm^{-3} (53.02 $\mu g/m^3$). Maxima values of $PN_{0.3–1}$ ($PM_{0.3–1}$) and $PN_{1–10}$ ($PM_{1–10}$) concentrations reached up to 2316.56 cm^{-3} (74.54 $\mu g/m^3$) and 24.45 cm^{-3} (125.35 $\mu g/m^3$).

Event 6 (Metal turning) was mostly associated with higher mean, median and maxima values of $PN_{0.3–1}$, $PM_{0.3–1}$ and $PN_{1–10}$ concentrations than Events 4, 5 and 7, which included other activities in addition to metal turning (Tables 2–5).For example, during Events 4, 5, 6 and 7 mean $PN_{0.3–1}$ ($PM_{0.3–1}$) concentration were equal to 60.79, 196.95, 222.59 and 88.05 cm^{-3} (1.71, 7.10, 9.17 and 3.16 $\mu g/m^3$), respectively, and $PN_{1–10}$ ($PM_{1–10}$) concentrations were 0.65, 3.78, 4.89 and 1.97 cm^{-3} (8.03, 43.67, 36.65 and 23.53 $\mu g/m^3$), respectively. This observation could be attributed to the fact that Event 9 occurred right after the performance of iron welding. However, no literature review has been found to support the above speculations or provide more information concerning particle number and mass concentrations of aerosol particles during iron sorting/drilling and metal turning operations.

Sowards et al. [81] used an electrical low pressure impactor (ELPI) to characterize the fumes produced by the shielded metal arc welding (SMAW) electrodes (E6010, E308-16 and E7018) and found that 95% of the welding fumes consisted of particles smaller than 0.3 μm for E6010 and E7018, whereas for E308-16, 95% of the welding fumes comprised the fume particles that were smaller than 0.6 μm. Those same authors also discovered that larger particles generated by the three electrodes governed the particle mass distributions expressed as mass median diameters between 0.55 to 0.75 μm [82]. Additionally, Zhang et al. [55] studied the exposure of workers to nanoparticles from a gas metal arc welding (GMAW) process by using a standard solid wire electrode (ER50-6, Qingdaohu Welding Material Company of Zhejiang Province, China). The Zhang group also reported that total PM_1 from a single GMAW event as defined by a filter-based Nano-MOUDI was equal to approximately 700 $\mu g\ m^{-3}$. This finding was similar to approximately 800 $\mu g\ m^{-3}$ obtained by Elihn and Berg [83] for GMAW workplace. Zhang et al. [55] also reported that the mean particle mass concentrations of particles in the size range of 100 nm to 1 μm for four welding points were

approximately 1600 ± 1030, 2380 ± 840, 2640 ± 1240 and 3120 ± 940 μg/m^3. Mean particle number concentrations of particles between 20 nm and 1 μm were approximately (1.82 ± 0.77) × 10^5, (2.29 ± 0.56) × 10^5, (2.94 ± 0.89) × 10^5 and (3.49 ± 0.66) × 10^5 cm^{-3}. Their outcomes were much higher than ours during Events 4 and 5 when rutile electrodes (E 6013) were used.

With respect to the literature on industrial processes research, Iavicoli et al. [51] observed that respirable particles (up to 4 μm) ranged from 35.4 to 192.3 μg/m^3 (mean ± standard deviation: 68.6 ± 69.1 μg/m^3) and from 97.9 to 125.4 μg/m^3 (mean ± standard deviation: 112.3 ± 11.4 μg/m^3) in the brazing station and the welding booth, respectively, of a mechanical engineering factory. Azarmi et al. [67] simulated a construction processes inside an indoor laboratory surrounding in order to investigate the release of and the exposure to coarse, fine and ultrafine particles. Their results showed that the mean PM_1 concentration was equal to 0.56 × 10^3 μg/m^3 and 0.63 × 10^3 μg/m^3 when the mixing of fresh concrete with GGBS (Ground Granulated Blastfurnace Slag) and PFA (Pulverised Fuel Ash) occurred, respectively. Additionally, a mean PM_1 value of 0.80 × 10^3 μg/m^3 for drilling and 0.86 × 10^3 μg/m^3 for cutting was recorded. Lin et al. [56] investigated IAQ in diverse work zones inside industrial manufacturing of fitness equipment and detected that the respirable fraction of particles fluctuated from approximately 3430–3920 μg/m^3 (mean concentration: 3690 μg/m^3), 170–410 μg/m^3 (mean concentration: 280 μg/m^3) and 220–790 μg/m^3 (mean concentration: 380 μg/m^3) during painting, manual welding and automatic welding, respectively. The size range of respirable particles while pouching (almost 40–110 μg/m^3) and cutting (approximately 60–90 μg/m^3) were found to be of the same order with Events 2 and 3. Nevertheless, the mean concentration during both pouching and cutting procedures were higher than the corresponding ones measured during Events 2 and 3; it was equal to 80 μg/m^3.

All the PN concentration values from Tables 1–4 were much lower than those reported in other studies. In particular, Mølgaard et al. [84] calculated a mean particle number concentration during working hours of 4500 cm^{-3} for particles between 8.5 nm to 9 μm inside a paint shop of a workshop.

Mean working particle number concentrations inside the molding room and the gluing area were equal to 36 000 cm^{-3} and 3300 cm^{-3}, respectively, for particles in the size range of 5.5 and 31 μm. Moreover, the mean total particle number concentration of particles between 0.007–10 μm was equal to 9610 ± 8757 cm^{-3} in the brazing station, whereas in the welding booth it was equal to 64 161 ± 34 554 cm^{-3} [51].

3.2. Particle loss and emission rates

Table 5 shows the particles number loss and emission rates for submicron (0.3–1 μm) and micron (1–10 μm) particles during the events inside the workshop area. Sometimes, it was not possible to estimate particle loss rate or emissions due to data limitation.

The highest particle loss rate for particles was during Event 2; it was 2.09 ± 0.07 h^{-1} and 2.11 ± 0.05 h^{-1} for particles in the diameter ranges of 0.3–1 μm and 1–10 μm, respectively. During Event 7, the particle loss rate was the lowest; 0.24 ± 0.01 h^{-1} and 0.35 ± 0.01 h^{-1} respectively.

The emission rates were generally higher for submicron (0.3–1 μm) particles compared to the corresponding rates for micron (1–10 μm) particles (Table 5). In particular, the emission rates of particles within the diameter range of 0.3-1 μm were the highest at 9.31 × 10^4 particles/h×cm^3 during Event 3, and the lowest at 5.74 × 10^4 particles/h×cm^3 during Event 1. In contrast, the emission rate of micron (1–10 μm) particles were the highest during Event 1 at 1008 particles/h×cm^3 and the lowest at 75 particles/h×cm^3 during Event 4.

As far as the authors are aware there are no published data on particle loss rate (i.e. infiltration rate and deposition rate) inside educational, and vocational training environments. However, there are several studies that presented air exchange and deposition rates separately. For example, the median air exchange rate in 25 naturally ventilated primary schools in Brisbane, Australia, fluctuated from 0.25 to 1.0 h^{-1} during non-school and school hours, respectively [87]. A study conducted in two

schools and one kindergarten in Kozani, Greece, found the mean air exchange rates to be 0.99 ± 0.64, 0.35 ± 0.45 and 0.36 ± 0.17 h^{-1}, respectively during the non-heating period. The same study found the mean air exchange rates were 0.46 ± 0.32, 0.05 ± 0.01 and 0.33 ± 0.25 h^{-1}, respectively during the heating period [88]. Guo et al. [89] found that the air exchange rate inside a primary during a 2-week measurement campaign reached the highest value of 7.92 h^{-1} when the windows were open and the air conditioning and fans were all on. The lowest exchange rate value 0.12 h^{-1} was observed when the windows were closed and both the air conditioning and the fans were off. Moreover, the air exchange rate in five classrooms of five schools located in different regions in Singapore ranged from 5.6 to 8.1 h^{-1} during occupied periods and from 5.0 to 6.1 h^{-1} during unoccupied periods [90]. Dorizas et al. [91] reported that the mean infiltration rates for nine naturally ventilated primary schools in the Mediterranean region (Athens, Greece) during spring ranged between 0.11 and 0.82 h^{-1}. However, two of these schools demonstrated high air exchange rate of approximately 8 h^{-1} due to air leakages from the older building constructions due to wind speed. Laiman et al. [87] recorded mean total particle number deposition rates for 25 primary schools in Brisbane of 102, 71 and 105 h^{-1} for grilling, printing and heating, respectively. Interestingly, the deposition rate of nano-diamonds inside a laboratory workplace fluctuated from 0.8 to 1.9 h^{-1} as a result of the air mass movement caused by the movements of the workers and the incomplete mixing of air [92]. Furthermore, Thatcher et al. [93] conducted experiments in a room of 14.2 m^3 with different types of furnishing and demonstrated the influence of the amount of furnishing and the airspeed of fans indoors had upon the deposition rates. Their findings regarded the dependency of deposition rate on particle size were consistent with the observations made by He et al. [94] for residences in Brisbane.

Moreover, Hussein et al. [73] reported there is limited awareness concerning emission rates of particles generated by indoor sources. They also pointed out the need to deepen the knowledge concerning this subject as it can be very difficult to understand. Nonetheless, Laiman et al. [87 measured the particle number emission rates for two naturally ventilated teaching classrooms in each

of 25 primary schools in Brisbane. The same group discovered that the mean particle number emission rates for grilling, printing, heating and cleaning activities (i.e. vacuuming, wiping tables, chairs and windows) were respectively $(2.51 \pm 0.25) \times 10^{11}$, $(5.17 \pm 2.00) \times 10^{11}$, $(8.99 \pm 6.70) \times 10^{11}$ and $(2.09 \pm 6.30) \times 10^{11}$ particles/min. The highest particle number emission rate among three different types of printers ("low emitter", "medium emitter" and "high emitter") inside a chamber was equal to 1.6×10^{11} particles/min, whereas the mean $PM_{2.5}$ emission rate of one office printer was 0.29 ± 0.07 μg/min [37]. Buonanno et al. [95] reported that $PM_{2.5}$ emission factors during exercise activities of pupils inside a school gym fluctuated from 1.5 to 8.9 mg/min. Moreover, PM_{10} chalk dust particles were emitted at rates that ranged between 8 and 14 mg/min while wiping the blackboard in a university lecture hall [96]. Additionally, Koivisto et al. [92] recorded maximum emission rates of nanodiamonds during assignments between 09:21–11:44, 12:38–14:35, and 14:36–15:23 equal to 6.1, 12.4 and 2.2 mg/min×m^3, respectively.

3.3. Exposure and inhaled deposited dose scenarios

The regional deposited dose of a male adult was calculated based on the hypothesis that during these events the workers/students performed light exercise. However, for comparison reasons regional deposited dose values during the activity of standing/resting were also reported. At this point, it needs to be pointed out that for our calculations the minute ventilation values during light exercise were adopted for the activity of walking 2.5 mph ≈ 4.0 km/h from Holmes [76] and Hussein et al. [74] and DF values during standing were adopted from the GMD (deposition) curve for resting from Hussein et al. [73].

Generally, as listed in Table 6, the total inhaled deposited dose of coarse particles (PM_{10}) for a male adult was the highest during Event 3 (Total deposited dose = 204.58 μg), followed by Event 2 (Total deposited dose = 132.31 μg) and Event 7 (Total deposited dose = 42.14 μg). Even though the mean particle mass of coarse particles (PM_{10}) during Event 3 was lower than the corresponding one

during Event 2, its duration was longer in comparison to Event 2, leading to higher total deposited dose of coarse particles (PM_{10}). As expected, the lowest total deposited dose of coarse particles was observed when Event 4 took place (Total deposited dose = 11.71 μg).

Individually looking at the regional deposited dose of coarse particles during all the events occurred in the workshop area, we noticed that the alveolar and the head/throat region received the majority and the lowest fraction of the total deposited dose, respectively (Table 6). Particularly, the deposited dose in the alveolar region and in the head/throat region corresponded to 53.03% and 18.18% of the total deposited dose, respectively, for all the seven (defined) events. On the other hand, if it is assumed that during all the events, the workers/students were only standing instead of performing light exercise, then the deposited dose in the respiratory system of a male adult will vary significantly. In this case, the total deposited dose will decrease by approximately 39.71%. Moreover, the deposited dose in the tracheobronchial and the alveolar region will decrease by almost 86.93% and 65.84%, respectively. Surprisingly, the deposited dose in the head/throat region will receive the largest fraction of the total deposited dose as it will increase by approximately 111.20 % (Table 6).

If it is also assumed that the workers/students carried out heavier exercises or activities which produced higher concentration of particles, then the deposited dose and thus, the exposure will be even more than what was calculated here.

There is no doubt that the exposure and deposited dose would be even higher if the educational building, hence the workshop area were located close to traffic, busy streets or centers of air pollution where the concentrations are exceptionally elevated [73–74].Therefore, the deposited dose in this research is an estimation of the minimum amount of the deposited dose in the respiratory system of a male adult during standing/resting and performing light exercise.

Another point that needs to be taken into account is that the deposited dose calculations were based on a healthy male adult. According to Anderson et al. [97], Kim and Kang [98] and Chalupa

et al. [99], the deposited dose in people with lung problems is expected to be larger than in healthy ones.

It should be kept in mind that the results obtained for the deposited dose in the respiratory system of a male adult in this study were based on estimations which took into account the particle mass of large particle (PM_{10}) calculated for all the events (apart from the undefined), the minute ventilation, the respiratory deposition fraction and the duration of each event rather on real-time model simulations or indoor aerosol models (IAM's).

Generally, IAM's have been widely used in exposure assessments as they save time, money and efforts than measurements and real-time model simulations [73–74].Furthermore, Hussein et al. [73–74] highlighted the importance of modeling the deposited dose in the respiratory system based on particle number, mass and active surface area as this approach could fill the gaps between exposure to and assessment of health effects of aerosol particles. For instance, the Hussein group applied a simple model in 2013 in order to calculate the total and the regional deposited dose based on particle number, mass and surface area of submicron particles in three age groups (teenagers, adults and elderly) [74]. Their results indicated that the daily total and regional deposited dose was higher in male adults than in females (based on any of the metrics). They also observed a slight difference in the values of the deposited dose in teens and elderly. Moreover, most of the deposited dose based on particle mass was accumulated in the alveolar region, whereas the tracheobronchial region received the smallest fraction of the total deposited fraction based on particle mass or surface area.

4. CONCLUSIONS

The particle number size distribution (0.3–10 μm) was measured inside an educational workshop, where conducted regular educational training and workshop tasks including iron welding and smoking, metal turning and iron welding. We focused on two different particle size fractions: (1) accumulation mode particles in the diameter range 0.3–1 μm and (2) coarse particles. Based on a

simple indoor aerosol model, we calculated the particle loss and emission rates inside the workshop during some activities. We also estimated the inhaled deposited dose in the respiratory system for a typical student or worker inside the educsational workshop.

We found out that the highest concentrations were observed during welding activities. For instance, mean $PN_{0.3–1}$ ($PM_{0.3–1}$) and $PN_{1–10}$ ($PM_{1–10}$) concentrations were about 1865.86 (54.49 $\mu g/m^3$) and 6.46 cm^{-3} (102.54 $\mu g/m^3$). During the same event, the highest particle loss rates for particles were documented, as well. On the other hand, maxima $PN_{0.3–1}$ ($PM_{0.3–1}$) and $PN_{1–10}$ ($PM_{1–10}$) concentrations were detected when iron welding took place, and later the operation of the exhaust fan and the activity of iron sorting/drilling occurred and they reached up to 4140.17 cm^{-3} (152.07 $\mu g/m^3$) and 25.36 cm^{-3} (456.28 $\mu g/m^3$). The emission rate was generally higher for submicron (0.3–1 μm) particles compared to micron (1–10 μm) particles. It is clear that the differences in the concentrations could be attributed to several factors: (1) type of activity (i.e. source specific) and (2) particle loss rate. However, further investigations are needed in order to confirm these speculations and to determine fully the physicochemical characteristics of particles measured in similar environments.

Based on our calculations for the inhaled deposited dose in the respiratory system, the alveolar received the largest fraction (~53.%) of the total deposited dose whereas the head/throat region received the lowest fraction (~18%).

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Table 1. Particle number concentrations [cm^{-3}] of submicron particles ($PN_{0.3–1}$).

Events	Description of events	Mean	Std. deviation	5%	25%	75%	90%	Min	Median	Max
Weekend	Unoccupied	31.49	12.01	14.46	20.91	40.86	48.29	12.51	30.59	64.08
Event 1	Iron welding & smoking	885.67	414.47	81.68	684.43	1145.23	1256.34	38.84	842.28	2316.56
Event 2	(Exhaust) fan & machine on, welding iron without (exhaust) fan running	1865.86	935.64	538.83	992.90	2613.33	3161.11	316.81	1958.63	3567.26
Event 3	(Exhaust) fan on, iron welding (with exhaust fan) & sorting/drilling	1494.77	938.23	471.58	625.50	2438.23	2709.96	443.92	1162.76	4140.17
Event 4	Making coffee & metal turning	60.79	37.56	22.52	29.01	83.43	120.15	21.54	50.69	158.02
Event 5	Metal turning & iron welding	196.95	45.94	131.17	171.06	233.10	261.37	117.54	181.12	296.98
Event 6	Metal turning	222.59	65.68	143.00	170.55	279.31	317.18	137.17	195.72	371.39
Event 7	Lecture & metal turning	88.05	10.01	71.48	81.16	94.33	100.15	67.26	89.74	109.41
Event 8	Undefined event	104.11	3.75	99.01	101.66	106.38	109.76	95.77	103.76	110.89
Event 9	Undefined event	152.39	27.29	99.84	150.12	160.79	169.91	86.44	155.95	244.38
Event 10	Undefined event	220.13	100.84	137.37	155.39	293.27	349.89	127.11	171.65	680.19

Table 2. Particle number concentrations [cm^{-3}] of micron particles ($PN_{1–10}$).

Events	Description of events	Mean	Std. deviation	5%	25%	75%	90%	Min	Median	Max
Weekend	Unoccupied	0.46	0.09	0.35	0.39	0.52	0.59	0.28	0.44	0.82
Event 1	Iron welding & smoking	4.46	3.57	2.20	2.91	4.48	7.39	2.03	3.49	24.45
Event 2	(Exhaust) fan & machine on, welding iron without (exhaust) fan running	6.46	4.33	1.53	2.68	9.28	13.12	1.14	5.80	16.92
Event 3	(Exhaust) fan on, iron welding (with exhaust fan) & sorting/drilling	4.96	4.32	1.17	1.67	7.82	10.16	1.01	2.93	25.36
Event 4	Making coffee & metal turning	0.65	0.16	0.49	0.55	0.71	0.86	0.46	0.61	1.36
Event 5	Metal turning & iron welding	3.78	1.14	1.51	3.45	4.44	5.00	0.78	3.54	6.26
Event 6	Metal turning	4.89	1.68	3.13	3.51	6.49	7.53	2.97	4.25	8.51
Event 7	Lecture & metal turning	1.97	0.44	1.27	1.59	2.24	2.57	1.16	2.05	2.94
Event 8	Undefined event	1.26	0.13	1.11	1.19	1.32	1.36	1.09	1.26	1.83
Event 9	Undefined event	1.95	0.21	1.64	1.80	2.07	2.17	1.45	1.98	2.59
Event 10	Undefined event	2.23	0.24	1.88	2.08	2.43	2.49	1.71	2.21	2.78

Table 3. Calculated particle mass concentrations [μg/m^3] of submicron particles ($PM_{0.3–1}$).

Events	Description of events	Mean	Std. deviation	5%	25%	75%	90%	Min	Median	Max
Weekend	Unoccupied	0.96	0.33	0.50	0.70	1.18	1.33	0.43	0.93	2.27
Event 1	Iron welding & smoking	24.95	13.83	3.25	17.95	31.49	34.60	1.64	22.52	74.54
Event 2	(Exhaust)fan & machine on, welding iron without (exhaust) fan running	54.49	30.76	13.73	26.01	77.43	98.79	8.21	54.80	116.75
Event 3	(Exhaust) fan on, iron welding (with exhaust fan) & sorting/drilling	44.16	31.32	12.15	16.25	73.47	84.33	11.41	31.11	152.07
Event 4	Making coffee & metal turning	1.71	0.98	0.74	0.88	2.28	3.24	0.71	1.42	4.32
Event 5	Metal turning & iron welding	7.10	1.98	3.92	6.07	8.72	9.77	3.17	6.50	11.20
Event 6	Metal turning	9.17	3.16	5.27	6.75	11.87	13.81	5.00	7.97	16.40
Event 7	Lecture & metal turning	3.16	0.39	2.49	2.84	3.50	3.63	2.43	3.21	4.00
Event 8	Undefined event	3.11	0.11	2.96	3.04	3.19	3.24	2.91	3.10	3.37
Event 9	Undefined event	4.45	0.71	3.02	4.41	4.74	4.89	2.69	4.62	6.65
Event 10	Undefined event	6.05	2.62	3.94	4.34	7.91	9.41	3.58	4.82	18.21

Table 4. Calculated particle mass concentrations [μg/m^3] of micron particles (PM_{1-10}).

Events	Description of events	Mean	Std. deviation	5%	25%	75%	90%	Min	Median	Max
Weekend	Unoccupied	3.97	1.70	1.94	2.73	4.77	6.26	1.09	3.62	12.77
Event 1	Iron welding & smoking	53.02	22.76	18.73	41.31	58.47	86.08	11.40	49.56	125.35
Event 2	(Exhaust) fan & machine on, welding iron without (exhaust) fan running	102.54	62.33	26.02	42.93	141.97	198.47	15.74	94.15	238.74
Event 3	(Exhaust) fan on, iron welding (with exhaust fan) & sorting/drilling	92.95	78.95	20.39	31.37	142.39	182.27	16.58	63.00	456.28
Event 4	Making coffee & metal turning	8.03	2.80	4.94	6.14	9.49	11.68	4.22	7.27	18.44
Event 5	Metal turning & iron welding	43.67	13.85	14.43	39.96	49.75	57.30	8.17	43.75	76.08
Event 6	Metal turning	36.65	10.25	23.38	27.09	46.72	50.81	19.76	34.80	55.09
Event 7	Lecture & metal turning	23.53	8.71	10.90	16.15	29.19	34.33	8.48	23.64	48.41
Event 8	Undefined event	16.80	3.22	12.47	15.00	18.17	19.49	10.67	16.68	28.66
Event 9	Undefined event	31.63	4.81	24.78	28.69	35.04	38.22	20.28	30.89	43.84
Event 10	Undefined event	36.15	6.69	24.93	31.13	41.12	42.90	22.72	36.23	52.85

Table 5. Particles loss rates [h^{-1}] and emission rates [particles/hour×cm^3].

	$PN_{1–10}$		**$PN_{0.3–1}$**	
	$\lambda+\lambda_d$ [h^{-1}]	**ER [particles/hour×cm^3]**	**$\lambda+\lambda_d$ [h^{-1}]**	**ER [particles/hour×cm^3]**
Event 1	1.31±0.08	1008	1.36±0.03	5.74E+04
Event 2	2.11±0.09	407	2.09±0.07	8.61E+04
Event 3	1.08±0.06	735	1.08±0.05	9.31E+04
Event 4	-	75	-	-
Event 6	0.64±0.01	135	-	-
Event 7	0.35±0.01	85	0.24±0.01	6.498E+04

Table 6. Deposited dose [μg] of large particles (PM_{10}) based on particle mass calculated for an adult male during all events (apart from undefined events).

Event 1 (Iron welding & smoking)		**Event 2 ((Exhaust) fan and machine on, welding iron without (exhaust) fan running)**		**Event 3 (Exhaust) fan on, iron welding (with exhaust fan) & sorting/drilling**		**Event 4 (Making coffee & metal scrubbing)**		**Event 5 (Metal scrubbing & iron welding)**		**Event 6 (Metal turning)**		**Event 7 (I metal scr**
Activities		**Activities**		**Activities**		**Activities**		**Activities**		**Activities**		**Activ**
Standing/ Resting*	Light exercise	Standing/ Resting*	Light exercise	Standing/ Resting*	Light exercise	Standing/ Resting*	Light exercise	Standing/ Resting*	Light exercise	Standing/ Resting*	Light exercise	Standing/ Resting*
(13.91)	6.59	(50.82)	24.06	(78.57)	37.20	4.50)	2.13	(10.03)	4.75	(11.11)	5.26	(16.18(
(1.36)	10.43	(4.99)	38.09	(7.71)	58.90	(0.44)	3.37	(0.98)	7.52	(1.09)	8.33	(1.59)
(6.56)	19.21	(23.97)	70.16	(37.06)	108.49	(2.12)	6.21	(4.73)	13.84	(5.24)	15.34	(7.63)
(21.84)	36.22	(79.77)	132.31	(123.34)	204.58	(7.06)	11.71	(15.74)	26.11	(17.44)	28.93	(25.41)

(*)The values indicated inside parentheses () of these activities will be only mentioned for comparison reasons.

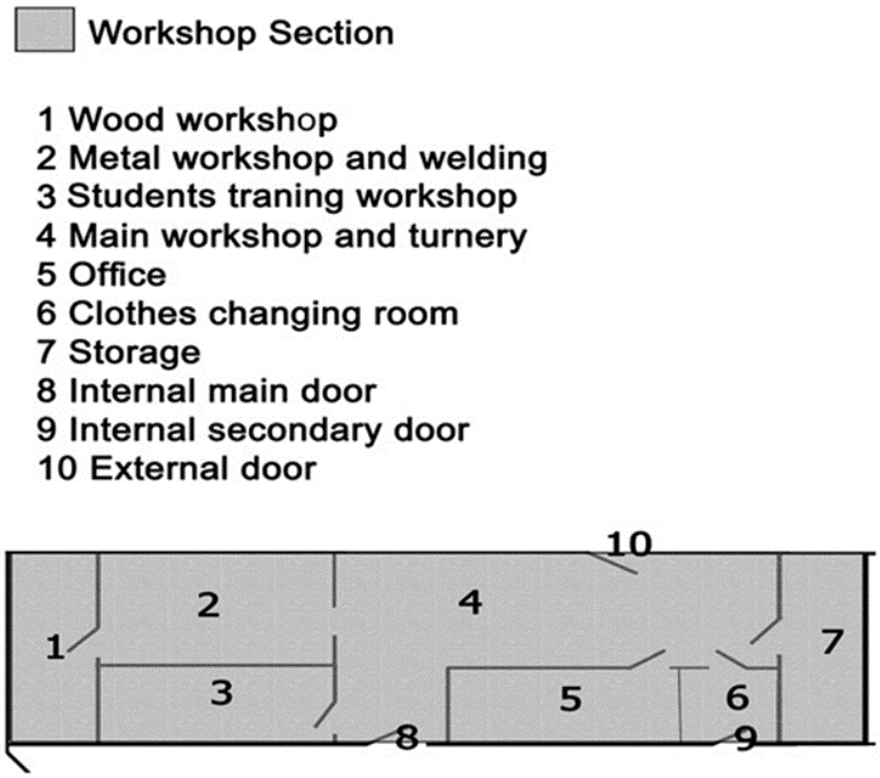

Fig. 1. A schematic chart of the workshop area of the Department of Physics.

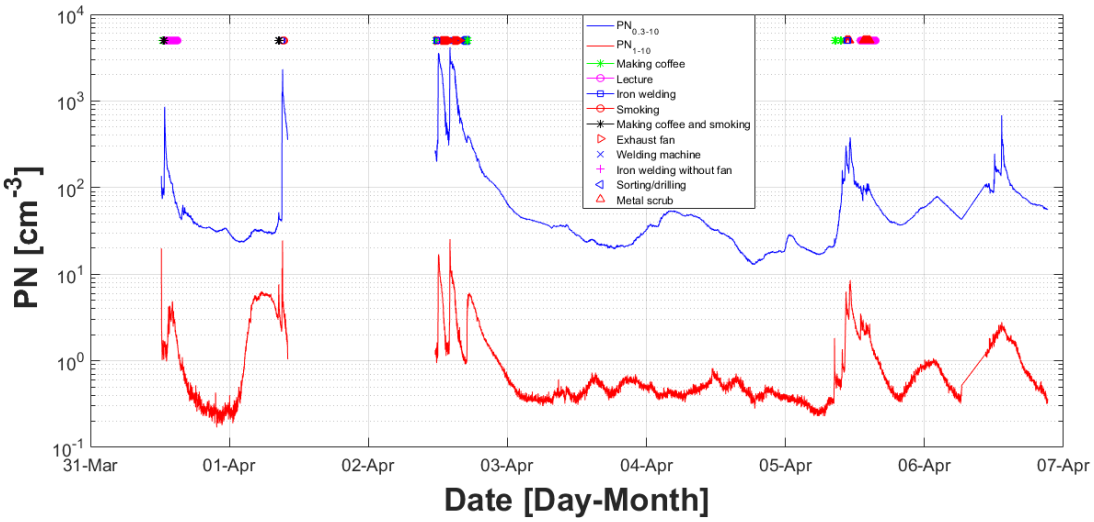

Figure 2. Particle number concentrations (Time series based on a 1-minute resolution).

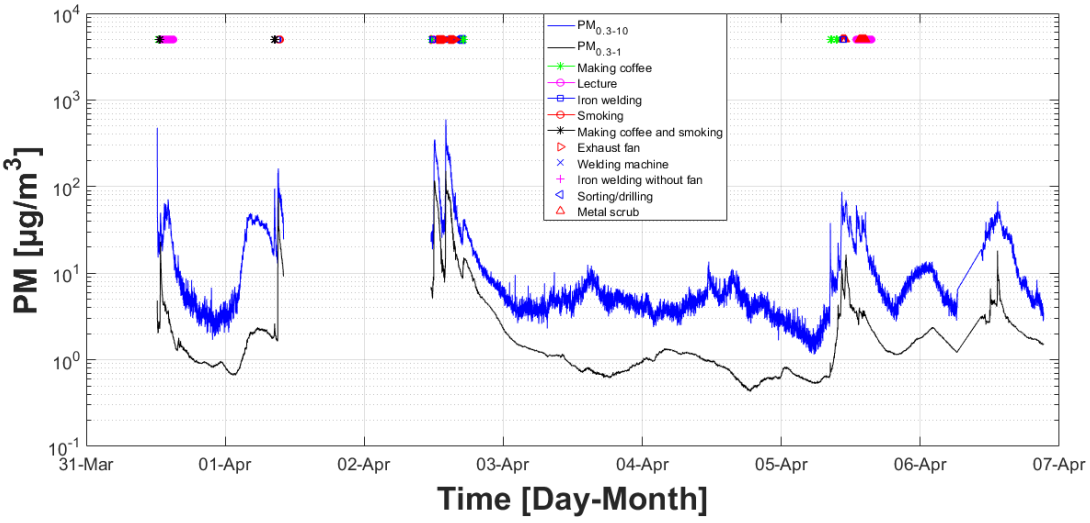

Figure 3. Particle mass concentrations (Time series based on a 1-minute resolution).

Supplementary information

Table S1. Description of each event and its duration during the weekend and the workdays.

Events	Description of events	Start	Stop	Duration (min)
Weekend	Unoccupied	3.4.2015 0:00	4.4.2015 23:59	2879
Event 1	Making coffee, smoking & having a lecture	31.3.2015 12:42	31.3.2015 14:38	116
Event 2	Making coffee & smoking	1.4.2015 8:29	1.4.2015 8:39	10
Event 3	Iron welding & smoking	1.4.2015 9:01	1.4.2015 9:46	45
Event 4	(Exhaust) fan & machine on, welding iron without (exhaust) fan running	2.4.2015 11:59	2.4.2015 13:24	85
Event 5	(Exhaust) fan on, iron welding (with exhaust fan) & sorting/drilling	2.4.2015 13:58	2.4.2015 16:23	145
Event 6	Making coffee	2.4.2015 17:00	2.4.2015 17:40	40
Event 7	Making coffee & metal turning	5.4.2015 8:30	5.4.2015 10:06	96
Event 8	Metal turning & iron welding	5.4.2015 10:11	5.4.2015 10:51	39.38
Event 9	Metal turning	5.4.2015 10:56	5.4.2015 11:48	52
Event 10	Lecture & metal turning	5.4.2015 13:20	5.4.2015 15:18	118
Event 11	Undefined event	6.4.2015 10:36	6.4.2015 11:13	37
Event 12	Undefined event	6.4.2015 11:55	6.4.2015 12:53	58
Event 13	Undefined event	6.4.2015 13:11	6.4.2015 14:21	70