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Indoor/outdoor particulate matter number and mass concentration in modern offices

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ABSTRACT

Indoor/Outdoor (I/O) particulate mass concentration (PM_{10}) and number concentrations were measured online in modern office environments with mechanical ventilation. The measurement took place during June 2014 in a building, which, belongs to the Norwegian Institute for Air Research, in Norway. Particle number size distribution was measured with an SMPS (0.014–0.7 μm) and an APS (0.5–18 μm) instruments, whereas, mass concentration was measured with a Dust-Trak II photometer. Two offices were selected to examine the outdoor contribution of particles and the influence of indoor sources. One office was fully occupied during working hours and the second one unoccupied at all times. The results suggested that human presence during the working hours affected considerably indoor particles in the occupied office both in terms of number and mass concentration compared to the non-working hours conditions. In the absence of any significant indoor source generating new particles (hardcopy devices), the indoor environment was influenced mainly from the presence of people with resuspension activities being the most important source for particle sizes larger than 1 μm. Moreover, indoor particle number and mass concentration was influenced substantially from outdoor sources. Generally, both indoor number and mass concentrations showed temporal fluctuations similar to those observed outdoors, suggesting that particle penetration was significant in both offices. However, low I/O ratio (90^{th} percentile < 0.3 for both offices) indicated the efficient removal of particles from the air filtration system.

1. Introduction

During the past two decades, indoor air quality has attracted the scientific interest since it influences human exposure to ambient particulate matter (PM) as well as gaseous indoor pollutants (CO_2, NO_2, volatile organic compounds). Common indoor environments, where people spend most of their time, include houses and workplaces. Although, PM characteristics and sources inside houses have been extensively studied, indoor particle behavior in commercial buildings is still a challenging area. Furthermore, human comfort and work performance are associated with indoor air quality in office environments [1,2].

It is well-known that airborne particles indoors may originate from outdoors or be generated indoors [3–5]. However, different indoor or outdoor sources are associated with different indoor environments. In regard to houses, indoor human activities contribute considerably to both indoor particle number and mass concentrations. These activities include e.g. cooking, vacuuming, burning candles, smoking, solid fuel combustion, walking [6–14] or even the use of electric appliances [15–17]. Work environments, on the other hand, are mostly affected by the use of office equipment [17–21]. However, in the absence of any significant indoor source, activities that resuspend particles from indoor surfaces are very common particle sources [22].

Hardcopy devices and especially printers generate particles at ultrafine size range [21,23] with almost no impact on mass concentration of particles [18,21]. He et al. [18] investigated different types of printers and found that the type of the printer is closely related with characteristics of particle emissions. Kagi et al. [19] studied chemical emissions from printers and found a considerable amount of volatile organic compounds released during the

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printing process. Printing speed, type of toner, number of printing pages, coverage of the paper [17,24,25] are factors strongly associated with emissions from printers. These characteristics make hardcopy devices a major pollutant for the indoor environment influencing further human exposure.

Nevertheless, the resuspension of dust settled on indoor surfaces is a matter of growing interest in the recent years. Indoor surfaces serve as a source of allergen-containing particles which can be resuspended by human activities [26–28]. Adverse effects on human health are associated with inhalation of these particles. Several studies focused on characteristics of particle resuspension in indoor environments or in chambers [7,29]. It was found that particle size plays an important role on resuspension with bigger particles resuspended easier [3,30–32]. Investigation of factors such as floor type, dust type, walking speed, floor loading, number of persons, type of shoes and environmental conditions (relative humidity, temperature) provided knowledge on the impact of different human behavior and indoor environment characteristics to particle resuspension [7,29,32–35].

A key role on indoor air quality of office environments is the location of the building along with the filtration system. Matson [36] found a decrease in ultrafine particle indoors (and outdoors) when moving from urban to rural areas. Quang et al. [37] measured higher indoor particle concentration in an office building close to a busway road compared to other offices. These studies highlight that the location of the building is a considerable factor when dealing with indoor air quality, since, penetration of outdoor particles through cracks and leaks is a major contribution to indoor particulate matter [4,38–41]. Ventilation of the building (natural or mechanical) is important and has strong impact on particle penetration from outdoors. In the case of natural ventilation, the building envelope serves as particle filter [42], where, infiltration from outdoors is controlled by particle size and building characteristics [43]. On the other hand, modern filtration systems prevent a considerable fraction of sub-micron particles to enter the building [37,44,45]. Hence, development of a suitable ventilation system can reduce human exposure to outdoor particles and improve indoor air quality in residential buildings [46].

The aim of the present study was to investigate particle number and mass physical characteristics in a modern working environment in the region of Scandinavia, where ventilation of the building is mechanically controlled. Indoor and outdoor concentrations were measured online in two offices with different occupation scenarios and technical characteristics in order to examine the contribution from outdoors as well as the influence of indoor sources in the indoor environment. Moreover, human occupation and infiltration of outdoor particles were investigated in respect to indoor concentration levels and particle size.

2. Materials and methods

2.1. Measurement location/office description

The location of the building is in a rural/suburban area 17 km northeast of the city of Oslo, Norway. It belongs to Norwegian Institute for Air Research and it is part of a science park surrounded by a residential area consisting of urban area and forest with several streets of medium traffic. A map of the location of the building is shown in Fig. 1. Several busses of public transport run through the area. Besides the vehicular traffic and domestic activities there are no other major sources in the vicinity of the area where the building is located.

The building has one main entrance at the front and a second one at the right hand side used for storage purposes. It is a three floor building, mainly consisting of offices and is separated into two

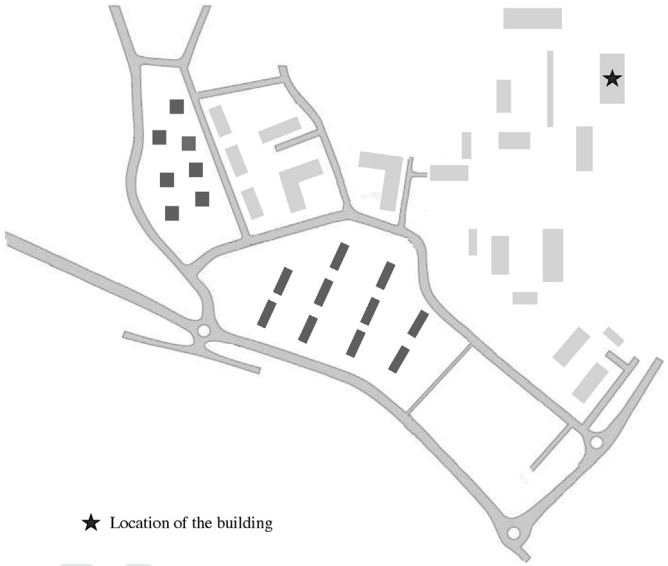

Fig. 1. Map of the location of the building under study and the surrounding area.

sections connected through an inside bridge. The frame of the building is constructed by bricks with a few areas covered by glass (mainly windows and doors). All offices are connected to outdoors with windows. The building is mechanically ventilated, although the windows in the offices can be opened at any time by the occupants. Smoking and burning candles is prohibited inside the building in all areas.

A few open areas cover the indoor space mainly belonging to the entrance hall and the laboratories. The laboratories are a mix of open space and small offices connected through corridors. Two offices were selected to perform the measurement, one at the first floor and one at the second floor. The office on the first floor is located inside a laboratory at the right section of the building, whereas, the office at the second floor is connected through a corridor with other offices located at the left section of the building. Figs. 2 and 3 provide the floor plan and the location for each office. Office A corresponds to the office at the second floor and office B corresponds to the office at the first floor. Office A faces the front of the building and is very close to the main entrance, whereas, office B faces the backside of the building. Several windows connect the two offices both with other indoor places and with outdoors. Fig. 4 presents a detailed scheme of the two offices.

Office A was furnished with shelves covered by books and papers, a desk with a computer and chairs. Blinds covered the windows at all times both the ones facing indoors and outdoors. The area of office A was 21 m^2 and its volume was 56 m^3. Office B on the other hand, was furnished with a long desk, one chair and shelves mostly covered with laboratory equipment. No blinds covered the windows. The area of office B was 16 m^2 and its volume was 40 m^3. Office A was connected to the main corridor of the section through a small office of the same width but smaller length, whereas, office B was directly connected to the laboratory through the door. The floor in both offices was covered with linoleum.

2.2. Experimental set up

Particle size distribution was measured with a TSI 3936 Scanning Mobility Particle Sizer (SMPS) and a TSI 3321 Aerodynamic Particle Sizer (APS). SMPS consisted of a TSI 3775 Condensation Particle Counter (CPC), a TSI 3080 Electrostatic Classifier (EC), a TSI 3081 Differential Mobility Analyzer (DMA) using a Neutralizer

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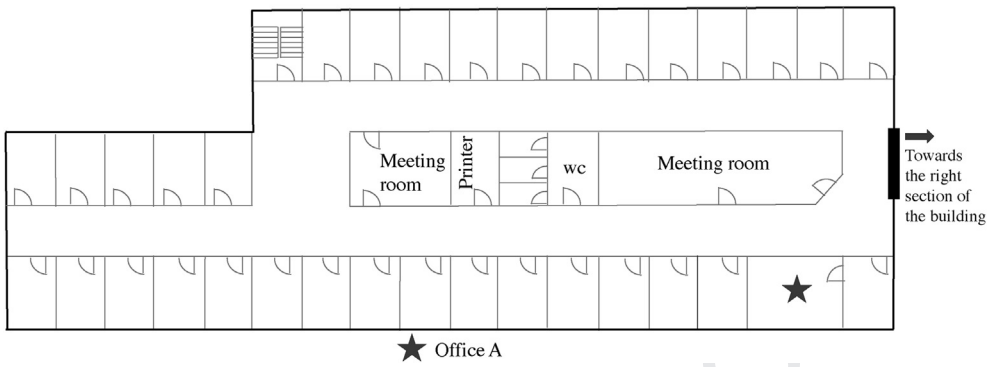

Fig. 2. Floor plan of the left section of the building. Location of office A.

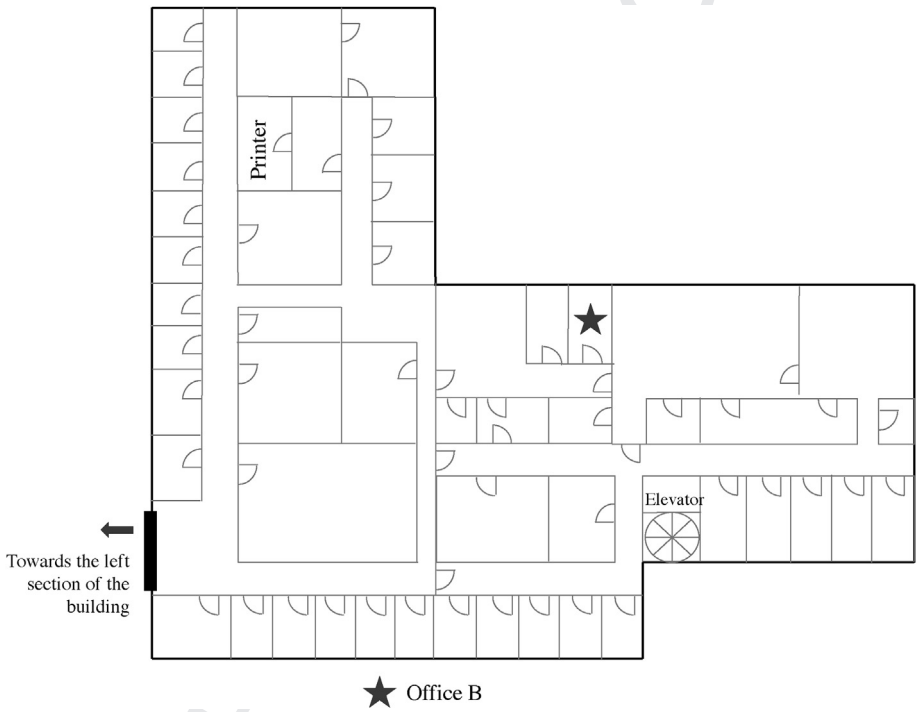

Fig. 3. Floor plan of the right section of the building. Location of office B.

Nickel-63 as a radioactive source. The SMPS measured particle number size distribution in the size range 14.6–685.4 nm in 107 channels and operated with sample flow rate at 0.3 L/min. The APS measured particle number size distribution of particles with aerodynamic diameter in the size range 0.5–18.4 μm in 51 channels with sample flow rate 1 L/min. Both SMPS and APS were set to log the data every 5 min. Additionally, PM_{10} mass concentration was measured with a TSI 8530 Dust - Trak II using flow rate at 1 L/min. The log interval was set to 1 min but 5 min average mass concentration was used in all calculations.

All instruments sampled from both indoors and outdoors using a system of tubes for outlets along with a switching valve, attached to the instruments. Two identical tubes of 1 inch diameter were connected with the valve in a straight line (one from the left and one from the right of the valve for sampling indoors and outdoors respectively) at 10–20 cm above the instruments. The frame of the window was replaced with a wooden one of exactly the same size. Outdoor sampling was succeeded by connecting the tube with the outdoor environment through a hole on the wooden frame. All gaps were sealed properly both from inside and outside the window. The switching of the valve was controlled by a computer connected with the instruments and an interval of 10 min was selected for sampling indoors/outdoors. The SMPS was scanning 150 s upward and 60 s downward every 5 min, whereas, the APS was scanning 150 s every 5 min. One minute and 30 s delay was used in order to separate the samples and flush the tubing after switching of the valve. Hence, a 10 min sampling from indoors with log interval 5 min was followed by a 10 min sampling from outdoors with the same log interval.

2.3. Office diary/indoor sources

The campaign was performed during June 2014, between 02 and 10/06/2014 in office A and between 10 and 13/06/2014 in office B. Office A was usually occupied during the working hours (08:00–16:00), whereas, no person was using office B. The latter was vacant during the measurements, thus, the indoor concentration was not affected by any indoor source induced by the human

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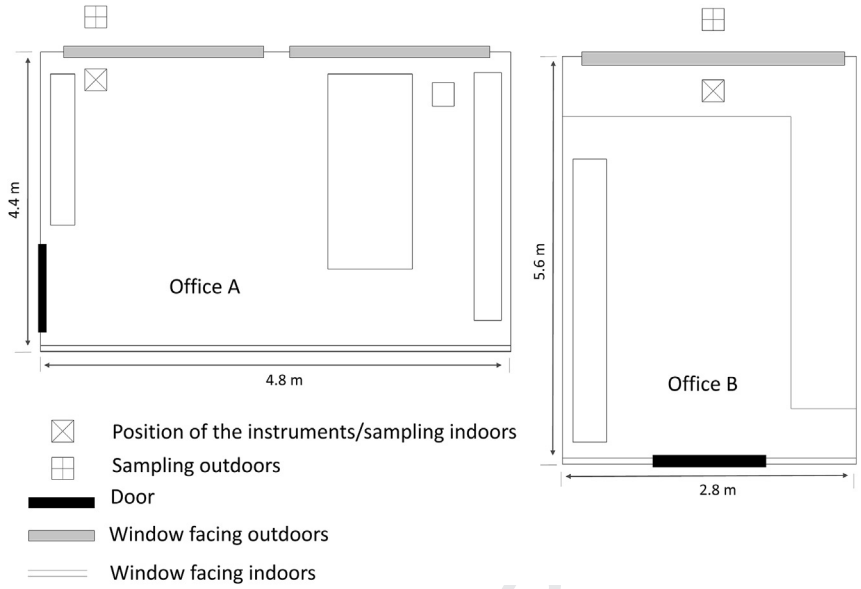

Fig. 4. Scheme of office A and B and position of the instruments.

presence. On the other hand, the occupants in office A used a diary in order to record all human activities. No printers or any other kind of office equipment that could generate particles were present in the two offices.

Table 1 presents the occupied hours during the working days in office A. At non-working days, the office was unoccupied at all times. It indicates that office A was usually occupied between 8 am and 4 pm with maximum 3 people present inside the office during the campaign. Moreover, for small periods (10–20 min) during the working hours the office was vacant. All activities, presence of people and opening of the door were recorded in a diary. No special activity was recorded, thus, the number of persons inside the office involves only the physical presence of the people.

One person was using office A permanently, while, several people visited occasionally the office during the working hours. The windows, both those facing indoors and outdoors, were closed at all times. However, the entrance door was selectively closed or open by the occupants. Since, no equipment was present inside office A, indoor sources include any kind of human activities that can be related with particle emissions or transport from another area of the building. According to Table 1, in the period 02-10/06/2014 during two of the typical working days (Monday-Friday) the office was vacant (03/06/2014 and 09/06/2014). Hence, the days when office A was occupied was on 02/06/2014 and on 04-06/06/2014 during the working hours.

Table 1
Occupied hours and number of persons in office A. Indication for number of persons corresponds to the range of people that were present in the office during the working hours.

Date	Day	Occupied hours	Number of persons
02/06/2014	Monday	begin of sampling - 16:00	1–3
03/06/2014	Tuesday	–	0
04/06/2014	Wednesday	08:15–14:00	0–3
05/06/2014	Thursday	06:45–16:30	0–2
06/06/2014	Friday	08:00–14:00	0–2
07/06/2014	Saturday	–	0
08/06/2014	Sunday	–	0
09/06/2014	Monday	public holiday	0
10/06/2014	Tuesday	08:00 – end of sampling	1

Office B, on the other hand, was vacant during the whole measurement period with the door always closed. However, one of the windows facing outdoors was slightly open for 1 h on 12/06/2014. Besides that, all other windows (both those facing indoors and outdoors) were closed during the measurements.

2.4. Ventilation/filters

The building uses a central ventilation system with different sub-systems serving at different parts of the building. The ventilation system is accompanied with heat exchangers and uses of district heating and cooling. The mechanical supply distributes the outdoor air from the ceiling. Glass fiber media filters are used, designed at airflow of 3400 m^3/h. The filters consist of several pockets where the air is distributed over the entire filter surface to achieve efficient removal of particles from the ventilation air. Particle efficiency of the filter meets requirements according to the European standard EN779:2002 for IAQ (Indoor Air Quality), where, the filters are classified based on the overall filtration (or collection) efficiency of liquid DEHS (Di-Ethyl-Hexyl-Sebacat) particles of 0.4 μm diameter. The filters used in the building have the overall filtration efficiency >80% and are replaced once per year. During the campaign the filters were approximately 6 months old.

Low-pressure drop filters are used before the technical installations in the building, whereas, higher-pressure drop filters are used before the redistribution of the air into the building areas. The mechanical ventilation of the building was on during 05:00–18:00 on Mondays and 06:00–18:00 on Tuesdays – Fridays, while, the ventilation was off during weekends.

3. Results and discussion

3.1. Indoor and outdoor particle concentrations

3.1.1. Particle number concentrations

Average values of the indoor and outdoor number concentration in the two offices are listed in Table 2a. The values represent the 24-h average concentration of each calendar day for offices A and B. Number concentration of particles was evaluated for particles between 0.014 and 0.5 μm (SMPS) and 0.5–18 μm (APS). The

Table 2
a) Daily average indoor and outdoor number (0.014–0.5 μm, 0.5–18 μm) and mass concentration (PM_{10}) in offices A and B, and b) average indoor number and mass concentration during working and non-working days and hours in office A.

a)

Date		0.014–0.5 μm (cm^{-3})		0.5–18 μm (cm^{-3})		PM_{10} ($\mu g/m^3$)	
		Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Office A							
02/06/2014	Monday	305	3287	0.14	2.47	1.8	18.0
03/06/2014	Tuesday	325	4488	0.08	1.82	1.0	12.1
04/06/2014	Wednesday	598	3503	0.16	1.34	2.1	14.1
05/06/2014	Thursday	356	4223	0.11	2.37	3.0	21.4
06/06/2014	Friday	290	2806	0.09	1.97	2.9	14.9
07/06/2014	Saturday	337	5137	0.03	1.25	2.9	15.8
08/06/2014	Sunday	331	3946	0.04	1.35	3.2	16.8
09/06/2014	Monday	389	5284	0.05	1.97	3.5	17.4
10/06/2014	Tuesday	601	6560	0.08	1.69	3.5	13.7
Office B							
10/06/2014	Tuesday	276	3624	0.026	1.07	1.0	11.2
11/06/2014	Wednesday	392	4784	0.050	2.72	1.5	18.3
12/06/2014	Thursday	158	5252	0.008	0.69	-[a]	3.1
13/06/2014	Friday	115	3782	0.002	0.24	-[a]	1.9

b)

	Working days	Non-working days	Occupied hours	Non-occupied hours
0.014–0.5 μm (cm^{-3})	430	346	769	333
0.5–18 μm (cm^{-3})	0.12	0.05	0.29	0.06
PM_{10} ($\mu g/m^3$)	2.7	2.7	3.4	2.6

[a] Values were excluded from the dataset. Instrument reached detection limit.

separation was based on the particle size range that each instrument measured and also considering that the SMPS measures the particle mobility diameter, whereas, the APS measures the aerodynamic diameter of particles.

In general, average indoor number concentration was higher in office A compared to office B. The daily average indoor concentration in office A ranged between 290 and 601 cm^{-3}, whereas, in office B the indoor concentration ranged between 115 and 392 cm^{-3} for particles between 0.014 and 0.5 μm. Accordingly, bigger particles (0.5–18 μm) showed higher concentration in office A than in office B. Daily average number concentration in office A ranged between 0.09 and 0.16 cm^{-3} during working days (02/06/2014, 04-06/06/2014), while, average indoor concentration for non-working days was significantly lower (0.03–0.08 cm^{-3}). Office B preserved lower indoor concentration with maximum daily average concentration at 0.05 cm^{-3}. The increased indoor concentration in office A is associated with the presence of people during the working hours and highlights the impact of indoor sources.

Additionally, a comparison between working and non-working days for office A is presented in Table 2b. A general remark is that the indoor number concentration during working days was higher than the non-working days, with an increase of 24% for lower (0.014–0.5 μm) and 140% for higher (0.5–18 μm) particle sizes respectively. However, in order to isolate the impact from the presence of people a comparison between occupied and non-occupied hours was introduced. The separation to occupied and non-occupied hours was achieved using the data from periods when office A was occupied or not (no person present inside the office) according to the diary. All occupied hours represent working hours. The average indoor number concentration for particles in the size range 0.014–0.5 μm, during occupied hours in office A, was 769 cm^{-3}, whereas, during non-occupied hours was 333 cm^{-3} corresponding to an increase factor of 1.3. Bigger particles (0.5–18 μm) were also substantially increased by a factor of 3.8 during occupied hours. Quang et al. [37] also found higher particle number concentration during working hours. Higher increased concentration measured for bigger particles during the occupied hours compared to smaller particles suggests that human presence is stronger for higher particle sizes (>0.5 μm) in the under study office.

Moreover, Figs. 5 and 6 compare the indoor with the outdoor particle number concentration in the two offices. In both cases, the indoor concentration was always lower than the outdoor. Outdoor number concentration of particles at 0.014–0.5 μm was usually one to two orders of magnitude higher with average number concentration outside office A 4268 ± 2419 cm^{-3} and outside office B 4613 ± 2514 cm^{-3}. On the other hand, average indoor number concentration for the same particle size range in office A and B was 383 ± 350 cm^{-3} and 253 ± 152 cm^{-3} respectively. The same characteristic is observed also for bigger particles (0.5–18 μm). The values suggest that indoor number concentration is significantly lower than the outdoor. This finding is in agreement with other studies were the indoor concentration of ultrafine particles is considerably lower than outdoor concentration in commercial buildings where smoking is prohibited [36,37,44,45]. Mechanical ventilation of the building prevents a considerable fraction of outdoor particles to be transported indoors and filters the indoor particle concentrations as well. Together with the building envelope, which operates as a natural particle filter, indoor levels of both fine and coarse particles are considerably reduced inside the two offices in respect to outdoor particle concentration.

In addition, Table 2 indicates that indoor number concentration for particles in the size range 0.014–0.5 μm inside both offices is elevated when outdoor concentration was increased as well. Thus, on 03/06/2014 where office A was vacant it is observed that the daily average indoor concentration is higher (325 cm^{-3}) than the previous day (working day). Similar finding is observed for Saturday, Sunday and Monday (07 - 09/06/2014), where the office was unoccupied at all times and the average daily concentration in each day was higher than on 06/06/2014 Friday (290 cm^{-3}) which corresponds to a working day. The same characteristic was not observed for bigger particles (0.5–18 μm), where, the values during working days were increased irrespectively of the outdoor particle characteristics.

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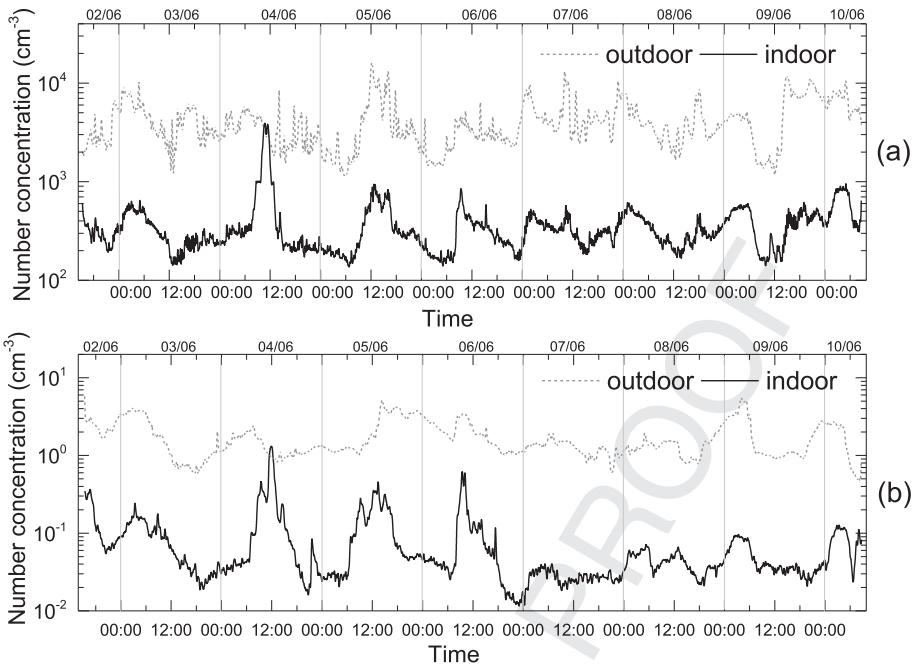

Fig. 5. Indoor and outdoor particle number concentration at office A (02-10/06/2014) for particles between: a) 0.014–0.5 μm and b) 0.5–18 μm.

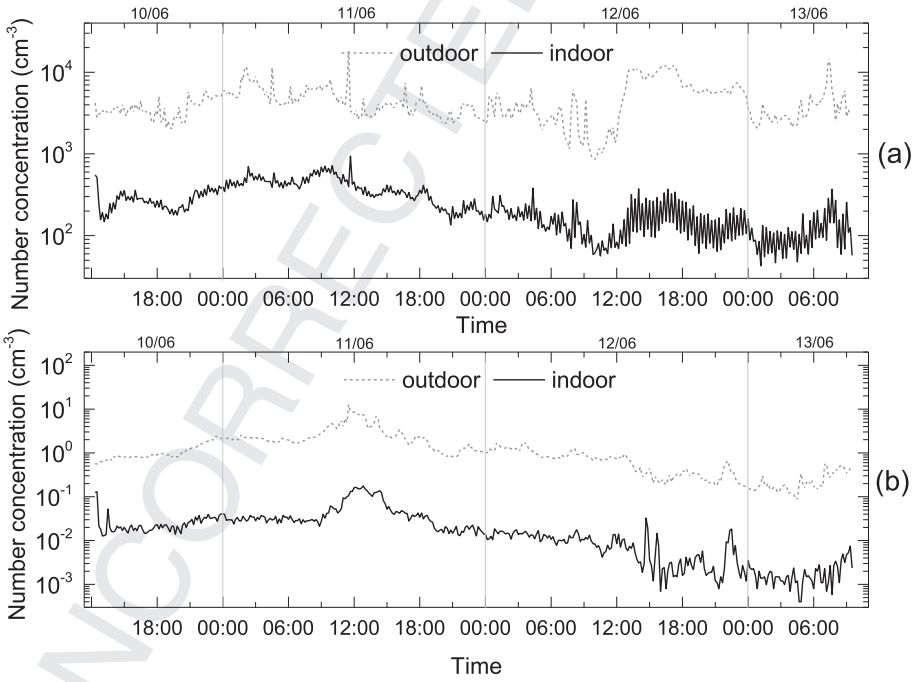

Fig. 6. Indoor and outdoor particle number concentration at office B (10-13/06/2014) for particles between: a) 0.014–0.5 μm and b) 0.5–18 μm.

3.1.2. PM_{10} mass concentrations

In general, considerable low levels of indoor mass concentration were observed in the two offices. The highest PM_{10} mass concentration was measured at 5.3 μg/m^3 in office A, while in office B it was at 3.0 μg/m^3. The numbers suggest slightly higher mass concentration in office A, probably due to human occupation, with no significant other indoor source. Moreover, the low indoor mass concentration, measured in both offices, is associated with the successful removal of outdoor PM_{10} by the filters while entering the building. Park et al. [45], has found that mechanically ventilated buildings can reduce exposure to outdoor particles up to 50%. Fig. 7 indicates that the outdoor PM_{10} concentration measured in the range between 3 and 41.4 μg/m^3 for office A, while for office B the concentration ranged between 1 and 42.6 μg/m^3. These values indicate substantially higher outdoor mass concentration than indoors and the efficient removal of a major fraction of outdoor PM_{10}. The daily average values of outdoor PM_{10} for both offices are reported in Table 2a. Higher outdoor PM concentration outside office environments, in the absence of any significant indoor source is reported in Sangiorgi et al. [41], and Quang et al., [37]. Finally, the

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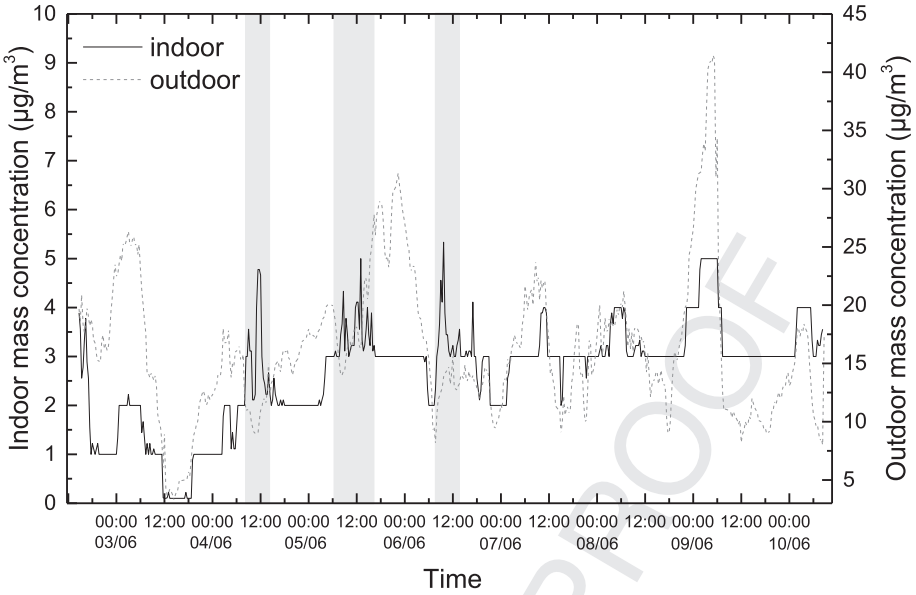

Fig. 7. Indoor and outdoor PM_{10} mass concentration in office A (02-10/06/2014). Colored areas represent occupied hours.

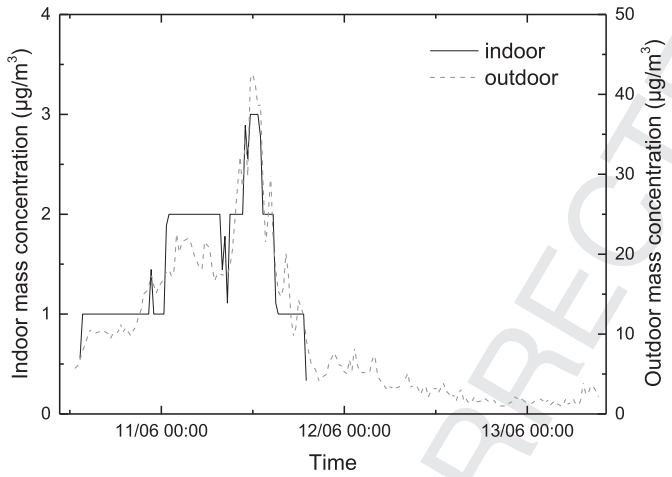

Fig. 8. Indoor and outdoor PM_{10} mass concentration in office B (10-13/06/14). Indoor data after 6 pm on 11/06/2014 reached very low concentrations close to the detection limit of the instrument and were excluded from the dataset.

comparable outdoor concentration confirms the influence of human occupation in office A, where higher PM_{10} concentration was observed.

No difference between working and non-working days was observed in office A (Table 2b) when comparing daily averaged concentrations, but this is due to effect of the averaged value used in the table. Therefore, average PM_{10} mass concentration was 2.7 μg/m^3 in both cases. Moreover, it is seen in Table 2a that the daily average indoor mass concentration is at similar levels for working (02/06/2014, 04-06/06/2014) and non-working days (03/06/2014, 07-09/06/2014). However, the impact of indoor sources is highlighted when comparing occupied and non-occupied hours (Table 2b). The latter had average indoor PM_{10} concentration 2.6 μg/m^3, while, the average indoor mass concentration during occupied hours was 3.4 μg/m^3 suggesting an increase of 31%. Higher indoor concentration of $PM_{2.5}$ during working hours in mechanically ventilated buildings is also reported in literature [37,47].

3.2. Indoor particle size fractions

Indoor number concentration was further divided into smaller size intervals and the fractions of each size interval were evaluated. The fraction of particles in each size interval was calculated by dividing the number concentration in the chosen size interval with the total indoor concentration (0.014–0.5 μm or 0.5–18 μm).

Fig. 9 presents the estimates at six different size intervals for the total measured range (0.014–18 μm) of the indoor and outdoor number concentration for both offices. The increase of the values from the size interval 0.5–1 μm in both plots is due to the different instrument used, thus, divided by different total concentration (0.014–0.5 μm or 0.5–18 μm).

Both plots (a and b) indicate that the indoor environment was dominated by particles in lower particle sizes in both offices. Thus, ultrafine particles (0.014–0.1 μm) was the size interval with the major contribution to particles in the range 0.014–0.5 μm, while, bigger particles were dominated by particles in the interval 0.5–1 μm. Moreover, the indoor number concentration decreased substantially while particle size increased, such that number concentration in the range 0.5–18 μm was considerably lower than in 0.014–0.5 μm. Figs. 5 and 6 propose that number concentration for smaller particles (0.014–0.5 μm) is at least two orders of magnitude higher than that of bigger particles (0.5–18 μm) inside both offices.

It is also important to note that indoor fraction for the size intervals 0.1 -.0.3, 0.3–0.5, 0.5–1 μm is higher than the outdoor for both offices. These results imply that infiltration of the particles at the size range between 0.1 and 1 μm is less effective and particles are able to penetrate easily indoors. On the other hand, the lower fractions obtained for indoor concentration (compared to outdoors) for particles < 0.1 μm and >1 μm relates with a higher removal of these particles by natural filtration (building envelope) and mechanical ventilation.

Additionally, Fig. 10 presents a comparison of the six size intervals between occupied and non-occupied periods in office A, in order to examine the contribution of indoor sources to particle size. Higher fractions during occupied periods were observed in ultrafine (0.014–0.1) and coarse (1-2.5, 2.5–18 μm) region. Thus, it is suggested that indoor sources contributed substantially at particle sizes lower than 0.1 μm and higher than 1 μm with a swift of indoor

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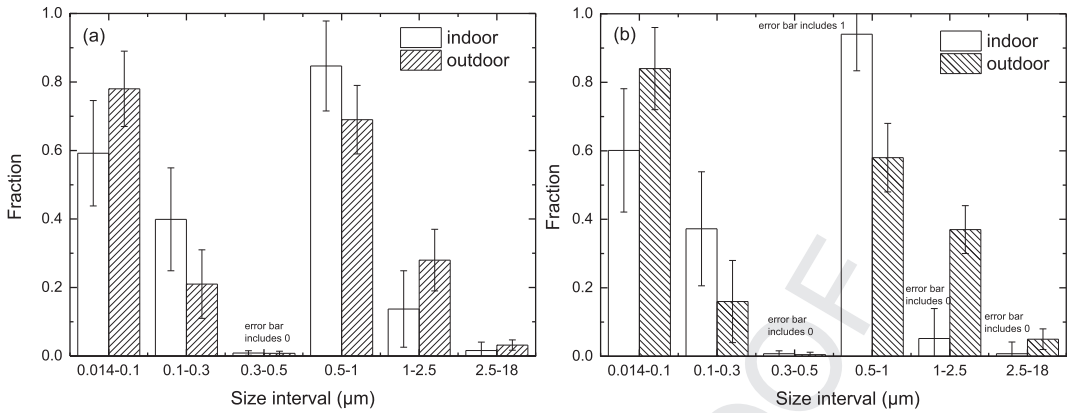

Fig. 9. Average fraction of indoor and outdoor particles in total concentration for different size intervals for: a) office A and b) office B. Error bars represent standard deviation.

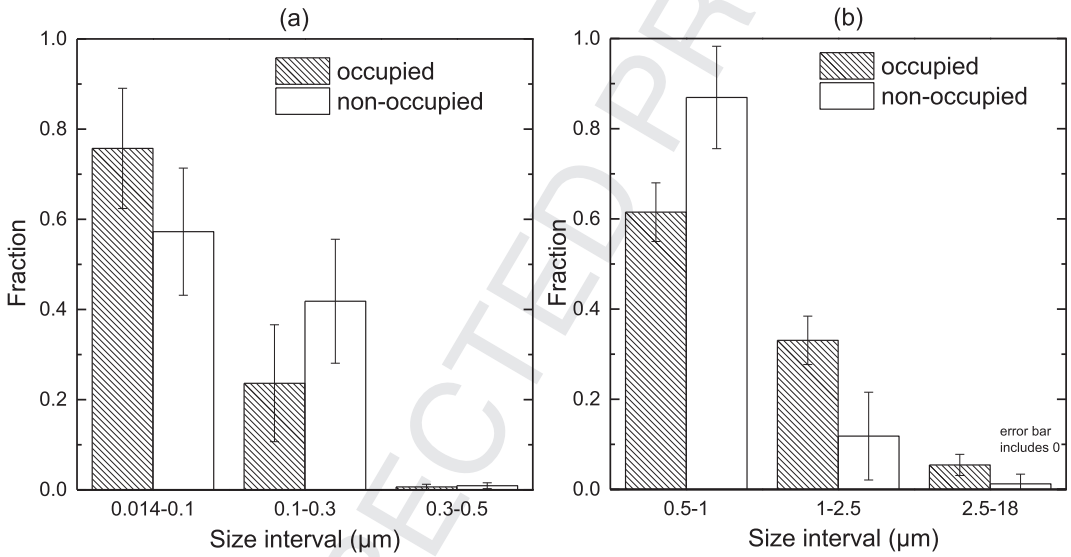

Fig. 10. Average fraction of indoor particles at different size intervals. Comparison between occupied and non-occupied periods in office A between: a) 0.014–0.5 μm and b) 0.5–18 μm. Error bars represent standard deviation.

particles at higher concentration at these sizes during the occupied hours. Indoor activities are usually associated with a wide range of particle sizes [22,48], depending on the origin of the indoor source. In the present case, the increased fraction in ultrafine region during occupied hours was mainly due to a major indoor source on 04/06/14 (Fig. 11), whereas, the increased fraction at particle sizes > 1 μm was associated with human activities causing particles resuspension.

On the other hand, fractions at accumulation size range (0.1–0.3, 0.3–0.5 and 0.5–1), preserve significantly lower fractions during occupied hours at all size intervals. The main reason is that the values in each case (0.014–0.5 μm or 0.5–18 μm) are related to the total concentration, thus, any change at a size interval highly affects the overall results.

3.3. Influence of indoor/outdoor sources

Indoor concentration in the two offices was affected by both indoor and outdoor sources. Particle number concentration as well as PM_{10} concentration showed considerable temporal fluctuations during day and night. Since, no source that could generate new particles to indoor air was present inside office A, indoor sources in this case include any kind of human activities during working hours, with most important being the resuspension of indoor particles [22,33,34].

Figs. 3–8 indicate a strong influence by the outdoor particulate matter indoors both in terms of number and mass concentration, when no major indoor source was present. Numerous studies have already highlighted the contribution from outdoor sources to indoor number and mass concentration [4,22,36,37,41,49,50]. In general, indoor particles both for number and for mass concentration data presented temporal fluctuations similar to the ones observed outdoors. Although, all windows with access to the outdoor air were closed (except 1 h on 12/06/14 in office B) during the measurement, Figs. 3–8 imply that there is an important penetration of outdoor particles inside both offices.

3.3.1. Office A

In total, office A was occupied for 4 days during the measurement campaign (02/06/2014, 04-06/06/2014). To determine the impact of human activities during the working days, Fig. 11 presents a comparison between working and non-working days of indoor concentration for different size intervals. Local maxima that correspond to increased indoor concentration are observed mainly

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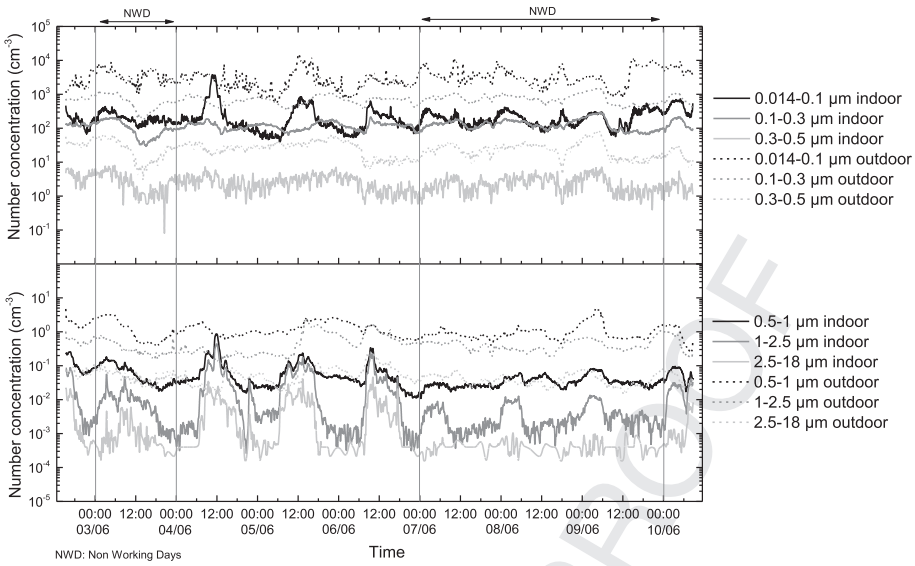

Fig. 11. Indoor and outdoor number concentration for office A at different size intervals (02-10/06/2014). Comparison between working and non-working days.

in the period 04–06/06/2014. The increased indoor concentration at these periods corresponds to working hours (08:00–16:00) and is associated with the presence of people. However, the increased concentration at these periods is not only due to human presence but is also highly influenced by penetration from outdoors. Fig. 5 denotes temporal increases of the outdoor concentration in the period 04 - 06/06/14 similar to the ones observed indoors. Indeed, outdoor particles penetrate indoors and influence the indoor concentration [39,43], but it is likely that infiltration of outdoor particles is strongest for particle sizes between 0.1 and 0.5 μm [4,42,51,52], whereas, human activities that resuspend indoor particles influence mostly higher particle sizes [7,22,29,32,33].

Particle number concentration at sizes >0.5 μm (especially for coarse particles > 1 μm) presents considerable temporal fluctuations during the working days (04-06/06/2014). All periods with increased indoor concentration were located during the working hours (8 am - 4 pm), while no similar behavior was observed outdoors (Fig. 11). In addition, Table 2a proposes that the indoor concentration during working days was considerably higher than that of non-working days. Daily average concentration ranged between 0.08 and 0.16 cm^{-3} during working days, whereas, during non-working days the daily average concentration did not exceed 0.0.8 cm^{-3}. It is, therefore concluded that during these periods the indoor concentration was highly affected by the presence of people with most probably resuspension of indoor particles as the main reason for increased concentration. On the other hand, indoor concentration of coarse particles outside the working days (07-09/06/2014) was mainly influenced by the outdoor environment, since the office was vacant.

Similar behavior was found for sub-micron particles, where the indoor concentration for particles in the size range 0.014–0.5 μm preserved temporal fluctuation as the one observed outdoors (Fig. 5a). This finding strongly associates the easier penetration of fine particles indoors compared to coarse particles. Table 2a suggests that during some of the non-working days sub-micron particles maintained higher average concentrations compared to working days such that on 03/06/2014 and 09/06/2014 the average indoor concentration (325 and 389 cm^{-3} respectively) was higher than the previous days (02/06/2014 and 08/06/2014). This behavior is associated with increased levels of outdoor concentration at non-working days, therefore influencing indoor concentration levels. However, an episode of highly increased number concentration was measured on 04/06/2014 inside office A, while, no similar increase took place outdoors (Fig. 5). Fig. 11 implies that the increased concentration corresponds to ultrafine particles (<0.1 μm), whereas, particles between 0.1 and 0.5 μm were not affected. Number concentration of ultrafine particles reached 3875 cm^{-3}, while the average number concentration of ultrafine particles inside office A was 255 cm^{-3} during the campaign. The numbers suggest an increase of indoor concentration by a factor of 15.2 compared to the average particle number concentration in office A. It is likely that this increase was provoked by an indoor source. However, according to the diary no special activity took place during the working hours. The recorded activities included only the presence of several people inside the office during meetings (maximum number of persons 3). Therefore, it is believed that the unusual high indoor concentration was transported from indoors. This assumption is supported by the fact that the door was open on 04/06/2014 until 13:00, along with the absence of any hardcopy devices inside the office, which are strongly related to ultrafine particle emissions [17,18,23,53].

In addition, PM_{10} mass concentration was affected by indoor and outdoor sources (Fig. 7). In the period 04-06/06/2014, which corresponds to working days, the indoor PM_{10} concentration was increased during 8 am to 4 pm in all three cases. Background concentration was between 1 and 3 $\mu g/m^3$, whereas, during the working hours PM_{10} mass concentration reached 4.8, 5 and 5.3 $\mu g/m^3$ on 04/06/2014, 05/06/2014 and 06/06/2014 respectively. One local but relatively lower increase of outdoor concentration was observed on 06/06/2014, during the occupied hours. However, it is believed that the indoor concentration was affected by both sources (indoor and outdoor), since indoor PM_{10} concentration reached values similar to those on 04/06/2014 and 05/06/2014, with outdoor concentration almost at the same levels (10–30 $\mu g/m^3$). Therefore, the increased PM_{10} concentration during 04–06/06/14 was associated with human occupation. On the contrary, in the following days (07-10/06/2014) indoor and outdoor PM_{10} concentration maintained similar temporal fluctuations, implying the significant impact of outdoor particles to the indoor environment. Outdoor PM are found to contribute to indoor levels in naturally ventilated spaces depending on factors such as wind, outdoor concentration and building openings [54,55].

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3.3.2. Office B

Particle number and mass concentrations in office B provide useful characteristics for particle infiltration from outdoors due to the fact that office B was not occupied during the whole campaign. It is evident from Figs. 6 and 8 that infiltration from outdoors was strong for the indoor environment. Indoor number concentration for particles <0.5 μm (Fig. 6a) is highly affected by the outdoor temporal fluctuations. Similar characteristic is observed for particles at higher sizes (0.5–18 μm, Fig. 6b).

In addition, mass concentration was found to depend considerably on outdoor concentration pattern. Fig. 8 indicates that PM_{10} particles indoors are in strong relationship with outdoor particles. The significant increase of indoor concentration level (11/06/2014) is associated with the same observation outdoors. Several studies have already examined indoor/outdoor relationship of PM and correlated the indoor concentration with the outdoor environment [45,49,56–60]. Although, values after 6 pm on the same day were excluded due to the very low measured indoor concentration (reaching detection limits of the instrument), it is important to note that the minimal concentration indoors was the result of the considerable decrease of outdoor PM_{10} concentration (from 43 μg/m^3 to 5 μg/m^3). Taking into account that the office was vacant and no indoor source was present. For this reason, we could not associate the opening of the window on 12/06/14 (for 1 h 14:30–15:30) with PM_{10} behavior but we have incorporated the results only with number concentration data.

The effect of the opening of the window to different particles sizes is shown in Fig. 12, where, the indoor particle number concentration at different size intervals in office B is plotted against time only for the day where the window was opened (12/06/2014). It is demonstrated that the opening the window had no effect on sub-micron particles (Fig. 12a). The colored area, which corresponds to the time-period when the window was open, suggests that indoor number concentration for all three size intervals (0.014–0.1 μm, 0.1–0.3 μm and 0.3–0.5 μm) presented no significant temporal fluctuation, rather than followed levels similar to the ones before (and after) opening the window. Hence, it is concluded that ultrafine particles penetrate easily inside the building regardless the window was open or not. However, the decreased concentration indoors for at least one order of magnitude in each size interval indicates the successful removal of a major fraction of outdoor ultrafine particles probably through the ventilation system.

A different behavior is observed for bigger particles (Fig. 12b). Number concentration of particles for the three size intervals (0.5–1 μm, 1–2.5 μm, 2.5–18 μm) increased immediately while the window was opened. This finding suggests that particles from outdoors at this size range enter inside the building resulting in a substantial increase of indoor concentration. It is well-known that particle penetration at coarse fraction is limited due to their relatively large size [40], therefore, the opening of the window resulted in easier penetration of coarse particles indoors. The present findings are in agreement with studies that estimate particle penetration from outdoors and contribution of outdoor sources [51,52].

3.4. I/O ratio

Indoor to outdoor ratio for both offices was significantly less than 1. Fig. 13a presents the I/O ratios using the number concentration data at different size intervals and Fig. 13b presents the I/O ratio for mass concentration data. Particles in the size intervals between 0.014 and 0.1, 0.5-1, 1-2.5 and 2.5–18 μm preserved higher ratios in office A than in office B. Since, I/O ratio is easily affected by indoor sources [36,47] it is likely that higher ratios observed in office A are due to office occupation. Higher I/O ratio in occupied buildings or offices is also reported in Quang et al. [37], and in Challoner et al., [47]. Ultrafine particles in office A were influenced by the indoor event on 04/06/2014, where considerably higher concentration was measured. On the other hand, higher ratios for coarse particles are associated with indoor resuspension activities.

A comparison between occupied and non-occupied hours for number and PM_{10} data is presented in Fig. 14. It is demonstrated that the I/O ratio is higher during occupied hours in all three cases with average ratio 0.22, 0.20 and 0.24 for number (0.014–0.5 μm, 0.5–18 μm) and PM_{10} respectively. Non-occupied hours presented substantially lower ratios with the highest average ratio 0.17 (PM_{10}). Additionally, Fig. 13a indicates similar ratios between office A and office B for the size intervals 0.1-0.3 and 0.3–0.5 μm. This finding is related with infiltration of outdoor particles. It indicates that building characteristics and ventilation system has the same impact for indoor particle dynamics, although measured at different offices. Low I/O ratios for particles >1 μm in office B are due to negligible indoor concentration at these size fractions (vacant office).

I/O ratio for PM_{10} particles presented similar characteristics with number concentration data, thus, office A was characterized by higher I/O ratios compared to office B (Fig. 13b). Moreover, it is observed that I/O ratio for PM_{10} is shifted to higher values

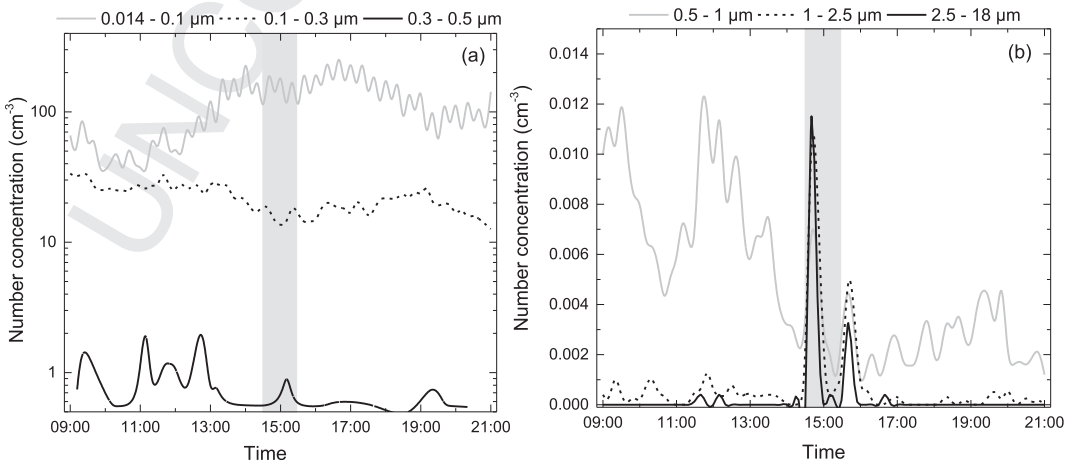

Fig. 12. Indoor particle number concentration in office B on 12/06/2014. Comparison between different size intervals a) 0.014–0.5 μm and b) 0.5–18 μm. Colored areas represent the opening of the window.

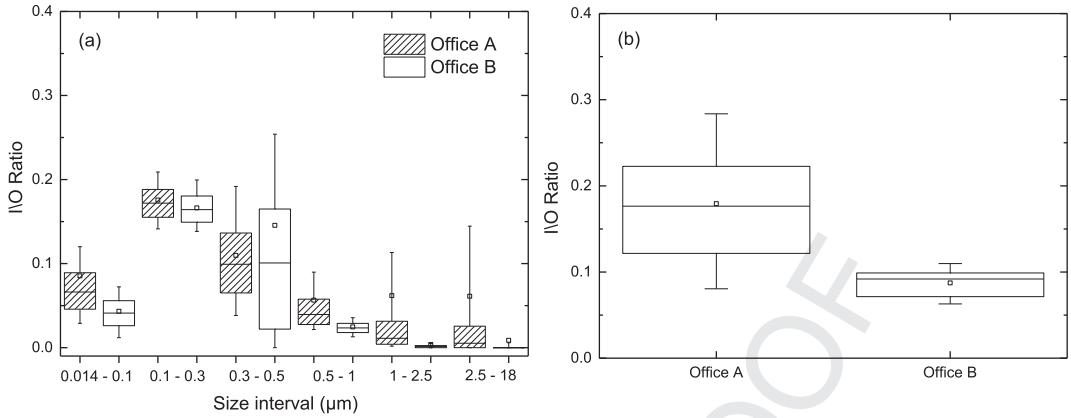

Fig. 13. a) I/O ratios of number concentration data at different size intervals, b) I/O ratios of mass concentration data. Comparison between office A and B. The box plots represent the 25th and the 75th percentile values, mean value and the horizontal line the median (50th percentile) value. The whiskers represents 10th and 90th percentile. Outliers are excluded.

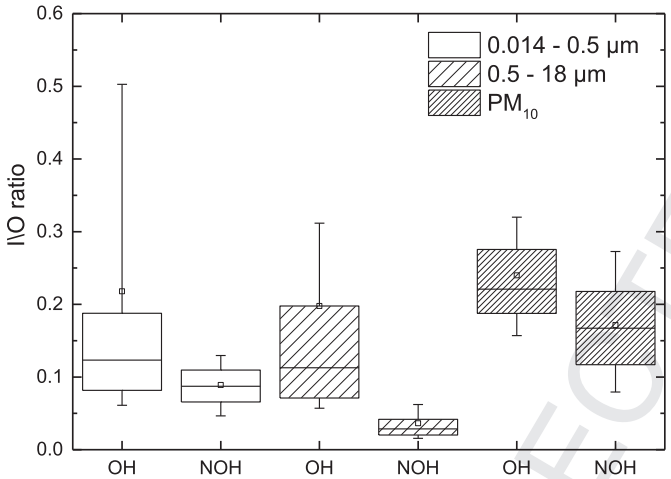

Fig. 14. Comparison of occupied and non-occupied hours in office A for number concentration (0.014–0.5 μm, 0.5–18 μm) and mass concentration data (PM_{10}). The box plots represent the 25th and the 75th percentile values, mean value and the horizontal line the median (50th percentile) value. The whiskers represents 10th and 90th percentile. Outliers are excluded.

compared to number concentration data with average I/O ratio at 0.18 for PM_{10} in office A, while, the highest I/O ratio for coarse particles was at 0.06 (1-2.5 and 2.5–18 μm). Several studies propose that human resuspension activities are associated with emissions at higher particle sizes (>$PM_{2.5}$) [3,22,32,35], which is in agreement with the presented results.

Additionally, Fig. 13a provides a relation between particle size and infiltration from outdoors. I/O ratios presented higher values for accumulation fraction (0.1-03 and 0.3-.0.5 μm) for both offices. Moreover, considerably lower ratios were found for particles >0.5 μm and for particles <0.1 μm. This finding is closely associated with particle dynamics, where, easier penetration and higher infiltration corresponds to particle sizes in the range 0.1–0.5 μm [61], whereas, infiltration of ultrafine particles is limited due to Brownian diffusion [62] and infiltration of coarse particles is likely less effective due inertial impaction and gravitational settling [52]. Several studies that examined the contribution from outdoor sources to indoors confirm our findings [4,36,41,43,49–52,63].

The numbers also suggest low I/O ratios in both offices (Fig. 13a and b). Low I/O ratios (<0.5) in a mechanically ventilated building are also reported in Ref. [44]. Despite the strong influence from outdoors, I/O ratio was usually less than 0.3. Median for particles <0.5 μm reached 0.17, while, for particles >0.5 μm the highest value was 0.04, indicating that a big fraction of outdoor particles remains outside the building (Fig. 13a). The values also suggest that enrichment of the offices at lower particle sizes (0.014–0.5 μm) are likely caused from penetration from outdoors, whereas, for bigger particles (>0.5 μm) infiltration from outdoors is considerably reduced due to efficient removal of coarse particles by the filters. The results also ensure that exposure to indoor PM and PN is substantially reduced compared to outdoor levels. Therefore, the ventilation system prevents the entrance of a major fraction from outdoors together with the building envelope that serves as natural particle filter when ventilation is off.

4. Conclusions

The present study focused on particle number and mass concentration physical characteristics in modern offices. The objective was to investigate the contribution of indoor/outdoor sources to indoor environment of a non-smoking, mechanically ventilated building. The results suggested that both outdoor and indoor sources have strong impact on indoor number and PM_{10} mass concentration.

No office equipment was present in the offices, thus, indoor sources included essentially the human presence. Increased PM_{10} mass concentration along with higher number concentration at particle sizes >1 μm during the occupied hours, ensured that resuspension of particles from indoor surfaces was the main contribution indoors. Only, one case of highly increased number concentration in the size <0.1 μm was measured indoors, however it was related with transport from another area of the building.

On the other hand, the simultaneous measurement of indoor and outdoor particle concentration provided a noticeable relation between the indoor environment and outdoor particulate matter characteristics. Both number and PM_{10} mass concentration were found to depend considerably on outdoor temporal fluctuations. However, the low obtained I/O ratios indicated low permitted particle fraction from outdoors. The low I/O ratios suggest the successful particle removal through the ventilation system as well as the behavior of the building envelope as a particle filter when mechanical ventilation was off.

The present study highlights that human occupation has strong impact in modern environments not only by generating new particle indoors, but also by resuspending the already deposited ones. It also triggers to improve building and ventilation characteristics

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in relation to particle penetration from outdoors, since human exposure to ultrafine and coarse particles is still a challenging area of indoor environments.

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