Indoor and outdoor measurements of ultra fine particles in a medium-size and large city

U. Matson*, L.E. Ekberg

Department of Building Services Engineering, Chalmers University of Technology, Sweden

ABSTRACT
The concentrations of ultra fine particles (UFPs) were measured in the medium-size city of Gothenburg, Sweden, in the large city of Copenhagen and at a rural site in Denmark. In Gothenburg, field measurements were conducted both in several residential and office buildings, while in Denmark measurements comprise two office buildings, one of them located at a rural site. Concentrations of UFPs were measured simultaneously indoors and outdoors. The results revealed that outdoor levels are major contributors to the indoor particle number concentration and the variability in concentrations is less pronounced indoors when no indoor sources are present. The magnitude of UFP concentrations is higher in the large city compared to the medium-size city. The results showed that in the Gothenburg office buildings the UFP concentrations indoors were fairly correlated to that outdoors. Another difference between Danish and Swedish offices is that in Denmark tobacco smoking is a main indoor source of UFPs. The results from a Swedish residential building show that the indoor concentration was strongly influenced by the indoor activity, e.g. cooking, ironing and by outdoor levels mainly during window airing.

INDEX TERMS
Condensation particle counters; Ultra fine particles; Field measurements; I/O ratio; Urban air

INTRODUCTION
Several studies have indicated significant health risks associated with exposure to particulate air pollution. Usually, particulate matter (PM) in health studies has been measured as the mass of particles smaller than 10 or 2.5 μm (IEH, 2000). Ultra fine particles (UFP), commonly defined as particles smaller than 0.1 μm in diameter, contribute very little to the overall particle mass, but are dominating in the number concentration (Keywood *et al.*, 1999). It has been shown that UFPs are able to penetrate deep into the lungs and have a relatively high deposition rate in the lower respiratory tract (Jaques and Kim, 2000). Toxicological studies show that UFPs can have a greater potency to cause adverse health effects than larger particles (Donaldson *et al.*, 1998; Johnston *et al.*, 2000; Oberdörster, 2001).

A number of researchers have studied the ratio between concentrations of airborne particles indoors and outdoors (I/O ratio) in order to assess the impact of outdoor contaminants on exposures indoors. The I/O ratio gives some information about the origin and transport of indoor particles. Most of these studies are focused on the fine and coarse particle fractions (Matson *et al.*, 2002;Monn *et al.*, 1997; Morawska *et al.*, 2001). However, there is only limited information available regarding the relationship of UFP levels indoors and outdoors. It is found that UFP events tend to be rapidly variable, and thus, the use of continuous instrumentation is required (Long *et al.*, 2000; Abraham *et al.*, 2002). Koponen *et al.* (2001) observed that indoor particle concentrations are highly dependent on the outdoor levels and the ventilation rate. The highest variability of UFPs indoors has been obtained during cooking (Riesenfeld *et al.*, 2000; Dennekamp *et al.*, 2002). Abt *et al.* (2000) studied the impact of indoor sources on the particle concentrations. The results indicated again that cooking contributed mostly to the UFP levels.

* Corresponding author. E-mail: uve@vsect.chalmers.se

This paper focuses on UFPs in two cities. The study was undertaken to investigate the relationship between indoor and outdoor particle number concentrations. The results presented here are obtained from a medium-size and a large city. In Gothenburg, field measurements were conducted in a residential and two office buildings, while in Copenhagen measurements comprise two office buildings.

EXPERIMENTAL METHOD

Instrumentation

During the study, two portable condensation particle counters were used to measure number concentrations of UFPs. These independently working devices are real-time single particle counting instruments. The measurements were carried out in the year 2002.

One of the condensation particle counters, TSI model CPC 3007, enables real-time particle number concentration measurements and data recording in the range from 0.01 to greater than 1 μm of diameter. Sampling data can be automatically logged at user-defined intervals. Data analysis can be made using the Aerosol Instrument Manager software supplied with the instrument. The maximum concentration with an accuracy of ±20% is 100,000 particles per cm^3. However, the instrument can be used to provide readings up to 500 000 particles/cm^3.

The other particle counter, TSI model P-Trak 8025, has the same working principle as the instrument described above. This instrument enables real-time measurement of particle number concentrations and data collection. For later retrieval the TrakPro Data Analysis Software is available. The particle detection range is from 0.02 to greater than 1 μm. The maximum measurable UFP concentration level is 500 000 particles per cm^3.

During the measurements, the instruments were placed indoors. Measurements were made simultaneously indoors and outdoors. For outdoor measurements, Tygon sampling tubes were used in order to decrease the particle losses in the tubes. They had a length of about 1 m and were put through a window.

Sampling Sites

The measurements were conducted at three locations in the Gothenburg area in Sweden, a city of 0.5 million inhabitants. In Denmark, two different measurement locations were chosen. The sampling sites were selected as follows: two offices in Denmark (C1 and C2); one apartment (G3) and two offices (G1 and G2) in Sweden. A summary of the sampling locations can be seen in Table 1.

Table 1 Type and location of investigated buildings

Location		Type	Smoking indoors	Measurement time and duration
C1	Large City, Denmark	Office	Yes	5 days, Oct. 2002
C2	Rural, Denmark	Office	Yes	4 days, Oct. 2002
G1	Medium-size City, Sweden	Office	No	3 days, May 2002
G2	Medium-size City, Sweden	Office	No	7 days, Aug–Sept, 2002
G3	Medium-size City, Sweden	Residential	No	6 days, June 2002

Site C1 is located at the centre of the Copenhagen city, with a population of 1.7 million. C1 is an office room situated on the fifth floor of a five-storey building near a street with high traffic intensity. The occupants of the room were non-smokers, however, in Denmark smoking is not forbidden indoors. An air change rate (ACH) of about 2 h^{-1} is provided by a mechanical exhaust system.

Site C2 is about 40 km away from the Copenhagen city in a rural location. C2 is an office room in a two-storey building located on the second floor. The nearest road is about 300 m away. The room was unoccupied, but the door was kept open during the measurements. With the door open, an ACH of about 2.8 h^{-1} is provided by a mechanical exhaust air system, and with the door closed the corresponding figure is less than 0.1 h^{-1}.

Sites G1 and *G2* are a few kilometres away from the centre of Gothenburg city, in the area of the Chalmers University of Technology. G1 is an office on the fifth floor in a five-storey building located about 300 m away from a busy street. The room has an ACH of about 1.6 h^{-1}. G2 is an office on the fourth floor in a four-storey building and the closest street is about 100 m away. The room has an ACH of about 3 h^{-1}. The air change in the buildings is provided by mechanical supply and exhaust air systems. Particle filters of the classes F5 (building G2) and F6 (building G1) are installed for filtering the supply air. Usually, the rooms were occupied with non-smokers (in Sweden smoking is generally not allowed indoors).

Site G3 is a few kilometres away from the centre of Gothenburg city. G3 is a one-room flat located in a four-storey building in the middle of a student village. The closest street is approximately 100 m away. The flat is situated on the third floor, where the measurements were conducted. Usually, the room was unoccupied during the day. The air change in the building is provided by a mechanical exhaust air system. The room has an ACH of about 1.2 h^{-1}.

RESULTS AND DISCUSSION

Indoor and Outdoor Concentration

A summary of the measured indoor and outdoor UFP concentrations, and the calculated I/O ratios is presented in Table 2. The indoor and outdoor values in Table 2 are averaged over the number of samples taken during the day. This results in a smaller magnitude of the particle concentrations, which may hide the short-term impact of high particle emissions as seen in Figure 1. When a strong indoor source of UFPs was present (e.g. tobacco smoking), high concentrations were temporally observed indoors. However, in the absence of indoor sources the variability of indoor concentrations can be expected to be much less pronounced than of those outdoors.

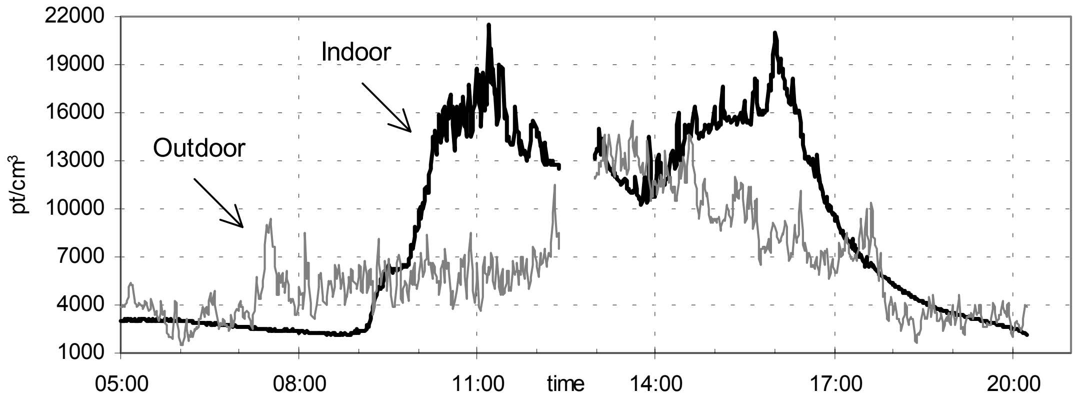

Figure 1 Simultaneous real-time indoor and outdoor measurements of UFPs in office at Site C2 conducted on Day 2. Total number of samples is 883.

Table 2 Daily number concentrations of UFPs and calculated I/O ratios in the five buildings studied

Site/ Day	No. of samples	UFP indoors, p/cm^3	UFP outdoors, p/cm^3	I/O ratio mean	I/O ratio, min	I/O ratio, max
C1-1	412	13319	17025	0.87	0.24	2.68
2	667	7996	13465	0.66	0.17	3.25
3	522	9479	12979	0.86	0.16	3.03
4	488	9416	13971	0.78	0.15	4.69
5	843	5816	7185	0.74	0.05	3.51
C2-1	884	3538	6183	0.67	0.19	1.33
2	883	8405	6333	1.33	0.26	4.51
3	893	2715	4422	0.82	0.21	2.79
4	497	4765	11517	0.68	0.07	2.48
G1-1	222	3954	7906	0.51	0.33	0.64
2	117	2857	5810	0.52	0.13	0.66
3	293	3816	9780	0.42	0.14	1.19
G2-1	836	4870	7061	0.72	0.30	1.20
2	805	4896	7005	0.69	0.14	1.19
3	787	3895	6122	0.68	0.10	1.06
4	859	3428	6699	0.63	0.19	1.07
5	458	2500	3949	0.72	0.15	2.13
6	859	3643	6445	0.62	0.12	1.56
7	869	3545	5449	0.73	0.13	1.66
G3-1	816	3424	6094	0.68	0.18	1.54
2	672	4439	6921	0.79	0.10	2.02
3	637	4105	3621	1.28	0.34	3.66
4	785	3557	3691	1.24	0.05	3.92
5	623	8415	5602	1.61	0.62	5.33
6	741	6409	7063	0.94	0.48	1.54

Among all measurements, the highest number concentration of UFPs both indoors and outdoors were observed at Site C1. The explanation for that could be the high traffic intensity as showed earlier (Hitchins *et al.*, 2000; Kittelson 1998; Nobel *et al.*, 2003). The highest daily average concentration indoors was obtained on day 1 while the lowest was found on day 5 as shown in Table 2. Outdoor average concentrations varied from 7185 to 17 025 particles/cm^3 and occurred in the same order as those indoors.

At Site C2, the average daily concentrations both indoors and outdoors were significantly lower compared to Site C1, expect day 2 when indoor concentration showed 8405 particles/cm^3 as the highest. This level seems to have been caused by an indoor source, like tobacco smoking, because the I/O concentration ratio is above 1. The lowest concentration indoors (2715 particles/cm^3) was found on day 3. The outdoor concentrations varied from 4422 to 11517 particles/cm^3.

At Site G1, the indoor concentrations of UFPs typically are lower compared to the other sites, having a minimum of 2857 on day 2 and a maximum of 3954 particles/cm^3 on day 1. Outdoor average concentrations varied from 5810 to 9780 particles/cm^3.

At Site G2, the average daily average concentrations both indoors and outdoors were similar to those observed at site G1, which was expected because of their close location and the absence of potential indoor sources in both buildings. The lowest concentration indoors was obtained on day 5 and the highest on day 2, 2500 and 4896 particles/cm^3, respectively. The outdoor concentrations varied from 3949 to 7061 particles/cm^3.

At Site G3, the average daily concentrations outdoors were slightly lower than in the other locations. However, the indoor concentrations were similar to those in C2, G1 and G2. On days 3, 4 and 5, the indoor values were higher than those outdoors, which highlights the type of building investigated. Consistently stronger contribution to the indoor levels seems to be due to the different activities performed indoors. The lowest (3424 particles/cm^3) and highest (8415 particles/cm^3) concentration indoors were obtained on days 1 and 5, respectively. The outdoor concentrations varied from 3621 to 7063 particles/cm^3.

Indoor–Outdoor Ratio

At sites C1, G1 and G2, indoor UFPs were fairly well correlated with their outdoor levels. In these cases, calculated I/O ratios were in the range from 0.66 to 0.87, 0.42 to 0.52 and 0.62 to 0.73, respectively. This suggests that the outdoor levels of UFPs are the main contributors to the indoor particle concentrations and also to the personal exposure. At site C2, three I/O ratios showed a good correlation ranging from 0.67 to 0.82, while the fourth one resulted in 1.33 probably due to an indoor source. At site G3, two of the I/O ratios were clearly below 1 (0.68 and 0.79), similar to those in C1. On three other days, the values were above 1, suggesting a strong contribution from indoor sources associated with particle generating activities like cooking, ironing etc. Only on day 6, the indoor and outdoor concentration ratio was close to 1 possibly due to open window. The lowest I/O ratio was found in G1, probably due to the comparatively high filter class (F6) in the supply air system.

CONCLUSIONS

- The UFPs generated outdoors are usually the major contributors to the indoor particle number concentration.
- The magnitude of UFP concentrations both indoors and outdoors is higher in the large city compared to the medium-size city.
- The variability in indoor concentrations of UFPs is less pronounced than outdoors in the absence of indoor sources.
- The indoor activities causing UFP production can increase the particle number concentrations to a higher level than outdoors.
- The lowest I/O concentration ratios were observed in the building with the highest class of supply air filtration.

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