Supplement

Scand J Work Environ Health 2004;30(2):54-62

Particle size characterization and the indoor-to-outdoor relationship of atmospheric aerosols in Helsinki

by Hussein T, Hämeri K, Aalto P, Asmi A, Kakko L, Kulmala M

Affiliation: University of Helsinki, Department of Physical Sciences, PO Box 64, FI-00014 Helsinki, Finland. markku.kulmala@helsinki.fi

The following articles refer to this text: 2004;30 suppl 2:9-18; 2004;30 suppl 2:73-79

Key terms: atmospheric aerosols; Helsinki; indoor; mechanical ventilation; outdoor; particle size; size distribution of particle numbers; ultrafine particle; urban aerosol

This article in PubMed: www.ncbi.nlm.nih.gov/pubmed/15487686

Original article

Scand J Work Environ Health 2004;30 suppl 2:54–62

Particle size characterization and the indoor-to-outdoor relationship of atmospheric aerosols in Helsinki

by Tareq Hussein, MSc,[1] Kaarle Hämeri, PhD,[2] Pasi Aalto, MSc,[1] Ari Asmi, MSc,[1,3] Leila Kakko, MSc,[4] Markku Kulmala, PhD[1]

Hussein T, Hämeri K, Aalto P, Asmi A, Kakko L, Kulmala M. Particle size characterization and the indoor-to-outdoor relationship of atmospheric aerosols in Helsinki. *Scand J Work Environ Health* 2004;30 suppl 2:54–62.

Objectives The influence of traffic and meteorological conditions on aerosol characteristics outdoors, the relationship between indoor and outdoor aerosol particles, and the pollutant transport indoors by means of a mechanical ventilation system were studied.

Methods Indoor and outdoor concentrations of fine-particle numbers were measured during the summer (15 May–30 June 2000) in one office located in the basement of a building in Helsinki, Finland. The total number concentration was measured with a condensation particle counter, and the particle number size distribution (7–600 nm) was measured with a differential mobility particle sizer. The size distribution (0.3–25 µm) of the indoor particle numbers was periodically measured with a laser particle counter.

Results Meteorological conditions, especially wind direction, had the greatest effect on the total number concentration and the size distribution of aerosol particles outdoors. The outdoor number concentration of ultrafine particles (diameter <100 nm) was strongly dependent on traffic density. The temporal variations in the indoor number concentration of ultrafine and fine particles (7–600 nm) closely followed the corresponding temporal variations outdoors. The building ventilation system was the main means of transporting aerosols indoors. The mean penetration factor was 0.41 (SD 0.11) for the nucleation mode (7–25 nm), 0.74 (SD 0.09) for the Aitken mode (25–100 nm), and 0.87 (SD 0.06) for the accumulation mode (100–600 nm).

Conclusions The ultrafine particles were bimodal with a nucleation mode (particle diameter <25 nm) and an Aitken mode (25 nm <particle diameter <100 nm). An accumulation mode was observed with a particle diameter larger than 100 nm. The patterns of fine-particulate air pollution inside an office can be largely estimated on the basis of the outdoor aerosol characterization and the mechanical ventilation system.

Key terms mechanical ventilation, size distribution of particle numbers, ultrafine particles, urban aerosols.

The properties of indoor-air aerosols are not well understood. In contrast, outdoor aerosols and pollutants have been extensively studied under different conditions and with the use of different measurement methods (1). In urban areas, local aerosol sources include road and soil dust, automotive fuel combustion, industrial processes, and energy production (2). Indoor sources include fungal spores, bacteria, dry insect fragments, animal dander, cooking combustion, fireplaces, kerosene heaters, and cigarette smoke (3). Emissions from consumer products and building materials can also be significant aerosol sources (4), as can the re-emission of deposited particles from indoor surfaces (5).

Many studies have shown that outdoor aerosols affect indoor-air quality (3). Outdoor-to-indoor particle transport can occur through cracks in the building shell and crevices in windows and doors (6). Ventilation systems are considered another critical factor in outdoor-to-indoor aerosol transport (7). For example, Jamriska et al (8) have shown that temporal variations in the number concentration of fine particles indoors follow those outdoors, but the actual particle number concentration is significantly lower indoors. Many studies have focused on mechanical ventilation systems and penetration mechanisms of particles, their aim being to improve indoor-air quality by means of better ventilation and filtration (7–9).

1 University of Helsinki, Department of Physical Sciences, Helsinki, Finland.
2 Finnish Institute of Occupational Health, Helsinki, Finland.
3 Ford Research Centre Aachen, Aachen, Germany.
4 University of Helsinki, Department of Agricultural Engineering and Household Technology, Helsinki, Finland.

Reprint requests to: Professor Markku Kulmala, University of Helsinki, Department of Physical Sciences, PO Box 64, FI-00014 Helsinki, Finland. [E-mail: markku.kulmala@helsinki.fi]

Urban populations in western countries spend 80–90% of their time indoors. Therefore, one of the main purposes of indoor aerosol studies is to contribute to the human exposure and health risk assessment of fine particles inside residences and workplaces and to discover means to improve indoor-air quality in these environments. This study is one of our investigations on submicrometer aerosol particles in Helsinki and other urban areas in southern Finland. Earlier, Buzorius et al (10) investigated the spatial variation in the particle number concentration of urban air in the Helsinki area. Väkevä et al (11) studied the vertical difference in the particle number concentrations between street and rooftop levels. Koponen et al (3) examined the outdoor-to-indoor relationships of the particle number and gas concentrations in an office building located in downtown Helsinki.

The principal objectives of our present study were (i) to investigate the relationship between indoor and outdoor aerosols and (ii) to identify the origins of fine (aerodynamic diameter <2.5 μm) and ultrafine (aerodynamic diameter <0.1 μm) aerosols by examining the indoor-to-outdoor (I:O) concentration ratio as a function of particle size. We investigated the relationship between ventilation operation and outdoor-to-indoor aerosol transport, the effect of traffic density on outdoor aerosols, and the effect of meteorological conditions on outdoor aerosols. We used three different instruments for measuring the number concentration and number size distribution of aerosol particles in order to cover the range from ultrafine to coarse (aerodynamic diameter >2.5 μm) mode particles.

Material and methods

Measurement site

The measurement site was located about 5 kilometers north of downtown Helsinki (figure 1). It was a typical suburban background area with minor local sources of air pollution except for traffic. One of the major highways in the Helsinki area was located about 100 meters from the building, and it provided a significant, temporally variable nearby source of aerosol particles. Another main road, located about 700 meters to the south, approached the main highway and crossed it at a distance approximately 1 kilometer to the southwest of the building. In addition, there were several small roads around the building. There was one new building being constructed in the neighborhood, located about 500 meters to the east of the measurement site, and another building construction site was located about 800 meters to the south. To the east, up to about 2.5 kilometers, the area consisted of extensive grass and agricultural fields. Beyond these fields, another main highway connected the eastern and western parts of Helsinki. This circular highway crossed the other main highways about 2.8 kilometers northeast of the measurement site. One of the main power plants was located in downtown Helsinki and another plant was about 20 kilometers to the east.

Room conditions and ventilation

The office building was a two-storey construction with clean air intake at about 2 meters above the ground level.

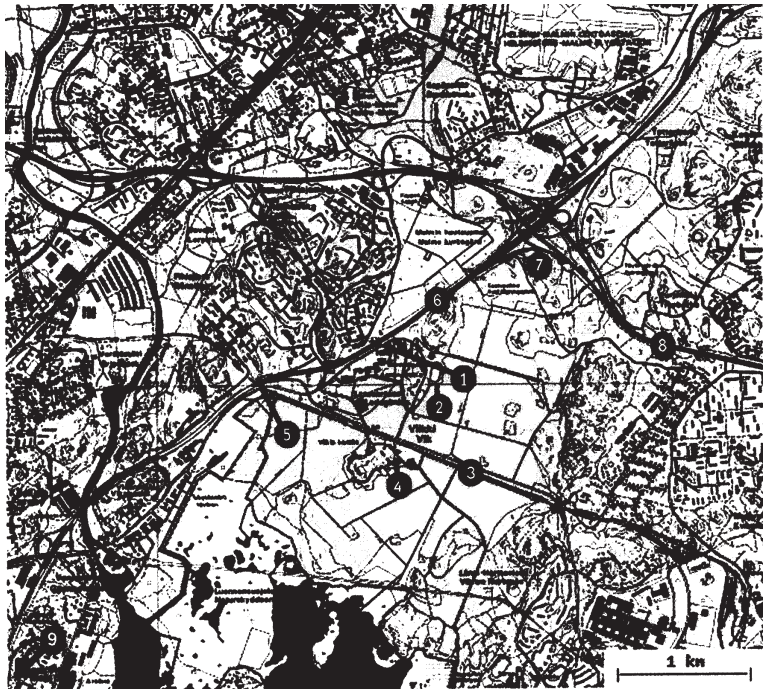

Figure 1. Measurement site location in Helsinki. Numbered black spot marks: (1) office building where the measurements were made, (2) nearby building construction, (3) nearest road to the south, (4) other building constructions, (5) nearest cross roads and highways, (6) main highway towards downtown Helsinki, (7) highway junction, (8) another circular highway connecting the eastern and western parts of the Helsinki area, and (9) major artery to downtown Helsinki. Published with permission from the National Land Survey of Finland (MAPSITE: available at http://www.kartta.nls.fi/; accessed March 2, 2001), permission number 126/MYY/02.

The selected office room was located in the basement and had no windows. The room had only one door, which was kept closed during the study period. The total volume of the room was 31 m^3. The office was not used during the measurement period.

The air was filtered and led to the room mechanically, and great care was taken to prevent any undefined airflows from entering the room. The ventilation system was equipped with an automatic mechanical air supply and exhaust controllers, and EU3-class filters had been installed on the air inlet. The settings of the ventilation system were kept unchanged throughout the measurement period. The airflow rate of the mechanical ventilation and the room temperature were monitored during the period of 8–20 June 2000. The mechanical ventilation operated continuously at a constant flow rate of ~26 l/s, which produced an air exchange rate of 3 h^{-1} into the room. The room temperature varied between 22 and 24°C during the weekdays, but during weekends it was 2–3°C higher.

Aerosol measurements

The particle number concentrations indoors and outdoors and the size distribution of the fine particle numbers were measured, with high time resolution, from 15 May to 30 June 2000. The indoor sources of air pollution were assumed to be negligible, apart from intermittent periods of intensive well-characterized cleaning. These periods were present on a small number of days, which were omitted from the present data.

The total number concentration of the aerosol particles was measured with a condensation particle counter (CPC) (CPC 3022, TSI Inc, St Paul, MN, USA), which was placed in a storage room next to the office. The air sampling was performed at 1-minute intervals from either indoor or outdoor air, using a computer-controlled valve system. The outdoor air sampling was performed near the fresh air intake of the mechanical ventilation system. Even though the sampling was performed as near as possible, the sampling line was 10 meters in length. An identical sampling line was used for indoor-air sampling to obtain a better comparison between the indoor and outdoor aerosols. Both sampling lines were made of copper with an 8-mm inner diameter. The air sampling was made at a flow rate of 1.5 l/min.

The size distributions of the fine particle numbers were measured with two identical differential mobility particle sizers (DMPS) assembled at the University of Helsinki according to the principles described by Adachi et al (12), Jokinen et al (13), and Birmili et al (14). The use of two identical systems enabled us to shorten the sampling lines significantly, which reduced the loss of nucleation mode particles in comparison with the CPC measurement. The air-sampling lines for the DMPS measurements were 2-m long copper tubes with an inner diameter of 4 mm. The sampling flow rate was 1 l/min. The particle diameter range covered with the DMPS setup was from 7 to 600 nm. The instruments were calibrated prior to the measurement campaign, and a systematic comparison, when both instruments were sampling the same air, showed good agreement for the particle number concentration (≤10% difference) with particle diameters larger than 12 nm. For particles smaller than 12 nm in diameter, the agreement was not so good due to potential artifacts.

A laser particle counter (CI-500, Climet Instruments Company, Redlands, CA, USA) was used in the indoor air measurements of the number concentration of the fine and coarse mode particles. The laser particle counter counted particles within the diameter range of 0.3–25 µm. In addition, this device measured room temperature and relative humidity. The sampling flow rate was about 2.8 l/min and the sampling time cycle was 10 minutes.

The size distributions of the particle number were described by a multilognormal distribution function (15) as follows:

$$\frac{dN}{d(\log(D_p))} = \sum_{i=1}^{n=3} \frac{N_{tot,i}}{\sqrt{2\pi}\log(\sigma_{g,i})} \exp\left[-\frac{(\log(D_p)-\log(\overline{D}_{pg,i}))^2}{2\log^2(\sigma_{g,i})}\right]$$

where D_p is the particle diameter and the three parameters required to identify individual mode i are the total number concentration N_{tot}, the geometric variance σ^2_g, and the geometric mean diameter D_{pg}, while n is the maximum number of possible individual modes. The least-square-fitting method was used to fit the measured particle number size distributions best to the multi-log-normal distribution function.

Meteorological conditions

In addition to the aerosol measurements already described, the Finnish Meteorological Institute (Helsinki, Finland) provided meteorological data on outdoor temperature and relative humidity, wind speed, wind direction, and rain. These data were important for the investigation of local pollutant transport over the city area. The meteorological data for the measurement period between 15 May and 30 June 2000 is shown in figure 2.

The outdoor air temperature varied between 8 and 20°C, and the relative humidity ranged between 40% and 100%. There was an overall increasing trend in both the temperature and relative humidity with time. The wind speed on most days was between 2 and 5 (range 1–10) m/s. The prevailing wind direction was primarily southwest (~225°), but it varied between east (90°) and north (360°). In the Helsinki area, colder air masses come from the north, while warmer air masses come from the south. This correlation between the temperature and the wind direc-

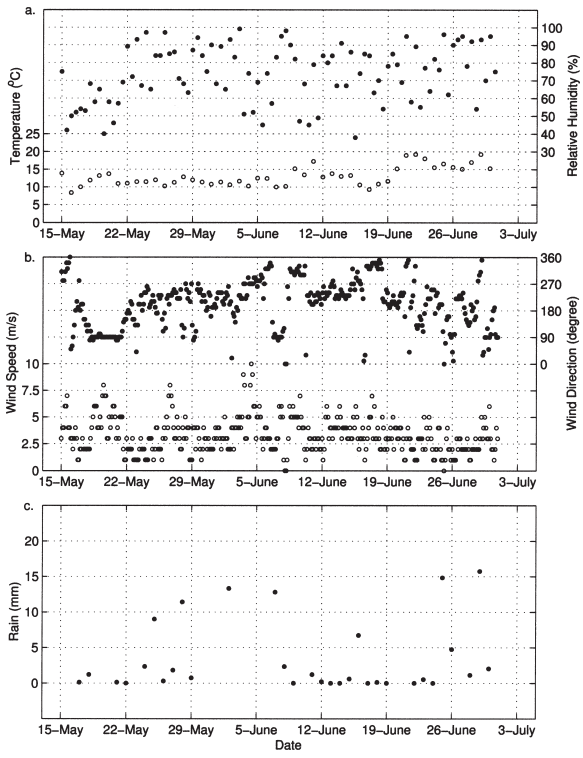

Figure 2. Meteorological conditions during the study period from 15 May to 30 June 2000: (a) 12-hour average outdoor air relative humidity (closed circles) and 24-hour average temperature (open circles), (b) 3-hour average wind direction (closed circles) and wind speed (open circles), and (c) daily rain fall.

tion could be seen also in our data. There were only a few days when the amount of falling rain exceeded 2.5 mm/day, which was considered to affect the aerosol number concentration significantly (figure 2).

Traffic density

The Finnish Road Administration provided the data on traffic density on the nearest highway. There were two different daily patterns, as shown in figure 3. On weekdays, two narrow peaks represented the morning (between 0600 and 0900) and afternoon (between 1500 and 1800) traffic rush hours, and the traffic was moderate between them. During early morning hours (between 0000 and 0400), the traffic density was higher on weekends when compared with that on weekdays, possibly due to leisure-time activities in the Helsinki downtown area.

Results

Total number concentration of aerosol particles

The total number concentration of the aerosol particles was obtained with two independent instruments. The CPC provided the total number concentration from direct measurements, but it was also integrated from the particle number size distributions measured with the DMPS. Typically, lower concentrations were measured by the CPC than by the DMPS, due to the long sampling lines in the CPC measurements, which increased the loss of ultrafine particles. Regardless of the difference in the absolute values, we observed similar patterns and temporal variations in the total number concentrations measured with the two methods.

Figure 4 shows the total number concentration of aerosol particles indoors and outdoors as measured with the CPC throughout the measurement period. The hourly averaged particle number concentration varied between 3000/cm^3 and 30 000/cm^3 outdoors, and between 1300/cm^3 and 20 000/cm^3 indoors. There was a decreasing trend in the total number concentration with time both outdoors and indoors, and this trend was probably due to an inverse relationship between the outdoor number concentration and the outdoor air temperature. On the other hand, the wind affected the total number concentration of the particles by transporting pollutants

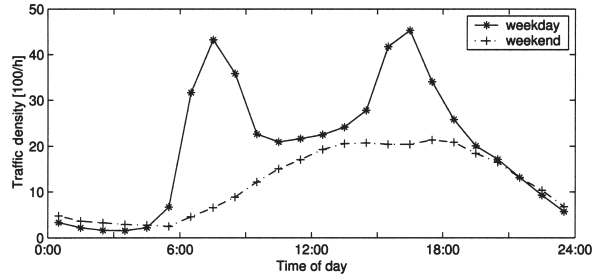

Figure 3. Diurnal patterns in traffic density on the nearest highway. Arithmetic means are shown separately for weekdays and weekends during the study period.

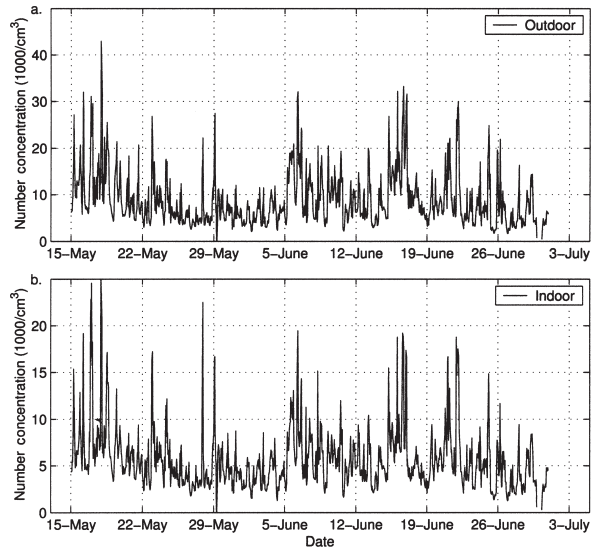

Figure 4. The 1-hour average total number concentration of aerosol particles as measured with the condensation particle counter outdoors (a) and indoors (b) during the study period from 15 May to 30 June 2000.

to the measurement site. For example, northerly winds were associated with higher particle number concentrations, due to the traffic on the highway, than the other wind directions were. The number concentrations were at their lowest during southerly winds and intermediate during easterly and westerly winds. The relatively small variations in wind speed and relative humidity did not seem to influence the total number concentration of particles outdoors. The rain caused a drop in the number concentration by cleaning the atmosphere, as can be seen from figures 2 and 4 (22 May–5 June and 26 June–1 July).

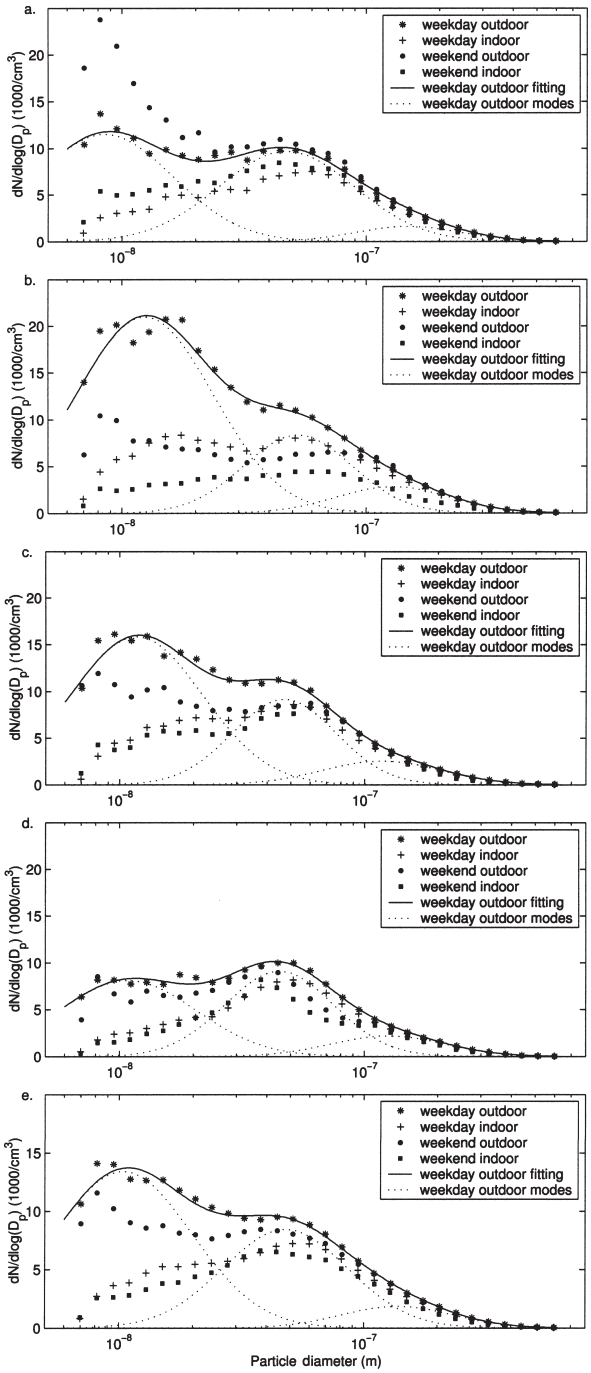

Figure 5. Mean concentrations of different sizes of aerosol particles in the size range 7–600 nm calculated from the average values for selected hours of the day during the study period. Separate outdoor and indoor concentrations are given for the weekdays and weekends: (a) midnight between 0000 and 0100, (b) morning between 0700 and 0800, (c) midday between 1100 and 1200, (d) evening between 1900 and 2000, and (e) the 24-hour average.

Size distribution of particle numbers

The temporal variation in the size distribution (7–600 nm) of the particle numbers and its dependency on meteorological conditions and traffic density were studied. The local wind direction had the largest effect on the size distribution pattern of the particle numbers, as the air masses, most likely, transported aerosols from different sources. Four sectors of wind direction were considered important in this respect. Sector 1 covered the angle ranging from –120° (240°) to 60°, which represented the main highway direction as the principle source of small particles from automotive engine emissions. This sector provided a high number concentration of aerosol particles, especially those <25 nm in diameter, with rapid temporal variations. Sector 2 was from the downtown area covering the angle ranging from 220° to 240°. Sector 3 was mostly eastern, covering the angle ranging from 60° to 170°. Sector 4, which represented the Baltic Sea region, covered the angle ranging from 170° to 220°. Sectors 2 and 3 represented long-range transported air pollution and local emissions of somewhat larger particles (from ~25 to ~60 nm in diameter) than sector 1. The integrated total number concentration of the particles was also lower from these two sectors than from sector 1. Winds from sector 4 provided a lower number concentration of larger particles (diameter >100 nm). The size range 12–100 nm in diameter was clearly represented during winds from sectors 1, 2, and 3, and, therefore, these occasions were considered to represent the local background aerosol in the urban and suburban areas of Helsinki.

Traffic density had a clear effect on the outdoor aerosol characteristics. The size distributions of the particle numbers varied with the time of day, and there was also a difference between weekdays and weekends. Figures 5a–5d show the hourly mean particle number size distributions on weekdays and weekends for selected time periods. Figure 5e shows the corresponding daily averaged data. At all times, the highest number concentration of outdoor air particles was observed in the size range <30 nm in diameter. Usually the outdoor number concentration of ultrafine particles (<0.1 μm in diameter) was higher on weekdays than on weekends. The only exception was Friday and Saturday nights (2300–0200), when the number concentration exceeded the weekday level (figure 5a). The outdoor

number concentrations during weekdays and weekends were at the same level only when the traffic densities were about the same (figure 5d). At all times, the indoor number concentration of ultrafine particles was clearly lower than that outdoors.

Modal characterization of aerosol particles

A lognormal fitting of the average particle number size distribution of weekday outdoor aerosols is shown in figures 5a–5c. In general, the three main modes (nucleation, Aitken, and accumulation) of aerosol particles were observed in the size range 7–600 nm in diameter both indoors and outdoors. The nucleation mode occurred in the particle diameter range 7–25 nm, the Aitken mode in 25–100 nm, and the accumulation mode in 100–600 nm. On weekends, the lower limit of the accumulation mode varied between 80 and 100 nm in diameter, and consequently the upper limit of the Aitken mode changed.

With the help of the measurement of the coarse mode particles indoors, we could construct a complete size distribution for the particle numbers that covered the size range from 7 nm to 25 μm in diameter. After this construction, the upper limit of the accumulation mode was extended to 1 μm in diameter, and we recognized the coarse mode that occurred in the size range >1 μm in diameter. Sometimes, we observed two nucleation submodes, probably due to high traffic densities. Nucleation mode 1 fell into the size range 7–12 nm, and nucleation mode 2 covered the size range 12–25 nm in diameter.

The geometric mean diameters of the recognized particle modes (nucleation, Aitken, and accumulation) are shown in table 1. The separation of the three fine particle modes was somewhat difficult due to the rapid temporal variations in the size distributions. The particle number concentrations in the three modes throughout the measurement period are shown for the outdoor air in figures 6a–6c and for the indoor air in figures 6d–6f. In the outdoor air, the highest number concentrations were observed in the nucleation mode, followed by those in the Aitken and accumulation modes.

Table 1. Geometric mean (GM) diameters and geometric standard deviations (GSD) of the particle modes from a lognormal fitting of the measured number size distributions of the outdoor air particles on weekdays and weekends.

	Particle mode					
	Nucleation		Aitken		Accumulation	
	GM (nm)	GSD	GM (nm)	GSD	GM (nm)	GSD
Weekends	10.0	1.8	41.0	1.9	110.0	1.8
Weekdays	10.8	1.8	43.5	1.9	125.0	1.8

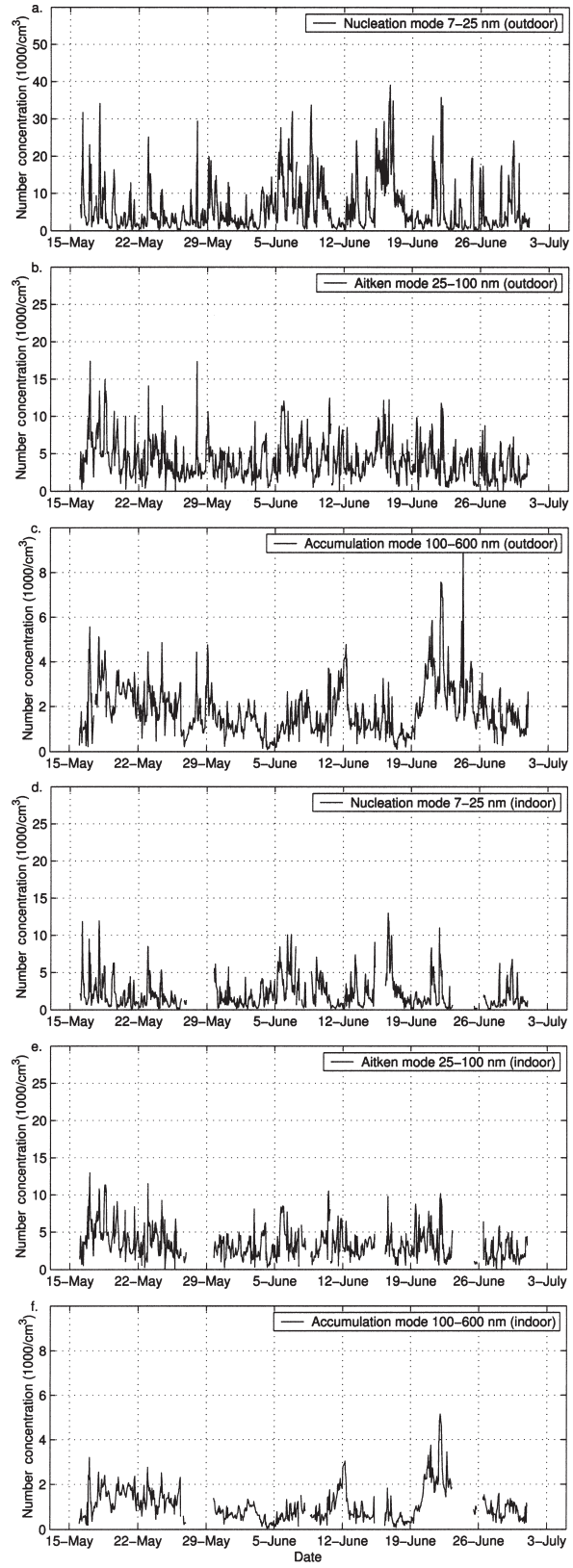

Figure 6 . The 1-hour average outdoor (a-c) and indoor (d-f) number concentration of aerosol particles in three modes during the study period.

Diurnal patterns in particle number concentration

The patterns of the particle number concentration both outdoors and indoors differed clearly between the weekdays and weekends, which probably reflected the differences in traffic density (figure 3).

Figure 7 shows the 1-hour average total number concentrations of aerosol particles during all weekdays (Monday–Friday) and weekends (Saturday and Sunday), as integrated from the particle number size distributions. The estimated number concentrations are also shown for each of the three particle modes. At midnight, the total number concentration of particles was higher during the weekends than during the weekdays, but otherwise the number concentration was lower during the weekends. During the weekdays, the morning rush hours and the daytime traffic increased the particle number concentrations in the nucleation and Aitken modes, while the accumulation mode was much less affected.

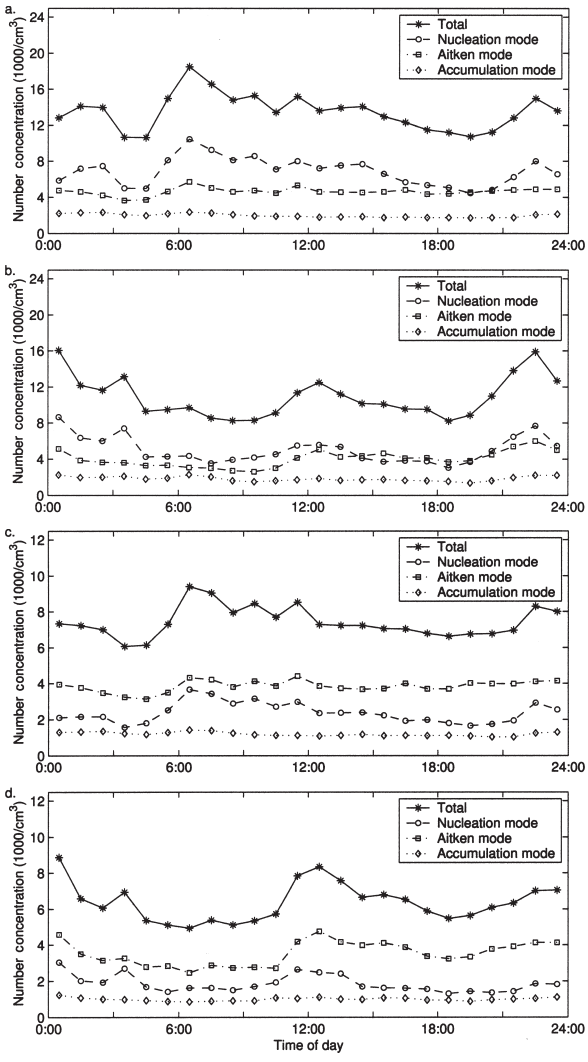

Figure 7. Diurnal patterns in the 1-hour average number concentrations of aerosol particles during the study period. Arithmetic means are shown separately for weekdays outdoors (a), weekends outdoors (b), weekdays indoors (c), and weekends indoors (d).

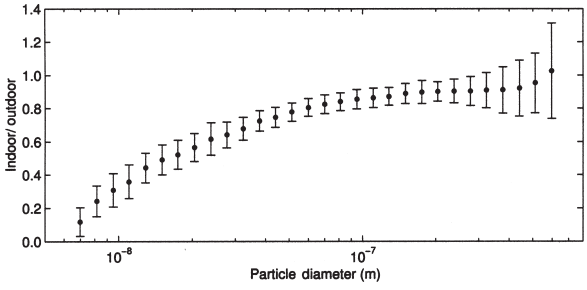

Figure 8. Indoor-to-outdoor concentration ratios during the study period. Arithmetic means and standard deviations are shown for different sizes of aerosol particles.

Indoor-to-outdoor relationship

The analysis of the I:O concentration ratios showed that the predominant source of indoor air particles was the outdoor air. The temporal variations in the indoor number concentrations of aerosol particles in the size range 7–600 nm followed closely the corresponding variations in the outdoor concentrations, as shown in figures 4, 6, and 7. The number concentration of the nucleation mode particles indoors was much lower than that outdoors, whereas the corresponding difference was not so large in the other two modes.

Figure 8 shows the I:O ratios as a function of particle size. The I:O ratios for each particle mode were rather constant throughout the measurement period, which was a logical occurrence due to the continuous operation of the mechanical ventilation system. The arithmetic means of the I:O ratios were 0.41 (SD 0.11), 0.74 (SD 0.09), 0.87 (SD 0.06), and 0.61 (SD 0.14) for the nucleation mode, Aitken mode, accumulation mode, and total number concentration, respectively. The channel-to-channel I:O ratio was higher than 0.8 for particles >100 nm in diameter.

Discussion

Our earlier study (10) demonstrated that the outdoor number concentrations of fine particles follow similar temporal patterns over a reasonably large area in Helsinki. The spatial differences affect mainly the absolute values that are lower in less urbanized areas. Therefore, we assume that the temporal patterns of the outdoor particle number concentrations in our study can be reasonably well generalized for the Helsinki area. Meteorological conditions, especially wind direction, had the largest effect on the particle number concentration. This effect can be expected to be similar in nearby suburban

and urban areas. In fact, it applies to a variety of meteorological conditions such as outdoor air temperature, humidity, wind speed, wind direction, and rain. In addition, rapid temporal variations in aerosol concentrations can be referred to exhaust emissions and the resuspension of deposited dust from road surfaces as a result of traffic (2, 10, 16), which also shows similar temporal patterns in different parts of the metropolitan area.

The outdoor and indoor fine particles were classified into the following three common modes according to the size range: nucleation mode (7–25 nm), Aitken mode (25–100 nm on weekdays and 25–80 nm on weekends), and accumulation mode (100–1000 nm on weekdays and 80–1000 nm on weekends). The particle number size distributions outdoors showed good general agreement with that described by Seinfeld & Pandis (15) for suburban areas. The modal classification was made according to lognormal fitting of the measured particle number size distributions, and it agreed well with the results of previous studies conducted in suburban and urban areas by Mäkelä et al (16), Birmili & Wiedensohler (17), and Koponen et al (3).

A major advantage of our modal classification was that it enabled local traffic-related aerosols to be separated from the other sources. The size distributions of the particle masses measured from diesel engine exhaust are nearly lognormal, the geometric mean diameters ranging from 60 to 120 nm, whereas those measured from gasoline engine exhaust tend to be asymmetric with smaller mean diameters, ranging from 40 to 80 nm (18). In our current study, on weekdays, the observed geometric mass mean diameters of the aerosol particles were 17.3, 80.7, and 200 nm for the nucleation mode, Aitken mode, and accumulation mode, respectively, while on weekends the corresponding values were 16.0, 72.3, and 176 nm, respectively.

The number concentrations of aerosol particles showed a clear diurnal pattern both outdoors and indoors (figures 5 & 7). The outdoor concentrations of ultrafine particles (corresponding to the nucleation + Aitken modes) seemed to be strongly related to traffic density, as indicated by the analysis of the influence of wind direction and the temporal pattern of concentration variations. This finding agrees with that of the study by Pakkanen et al (19), who compared an urban site with a remote area in Helsinki. They observed an Aitken mode with average mass mean diameters between 85 and 106 nm at both sites. Moreover, the analysis of ionic and elemental compositions in several fine particulate subfractions suggested that the Aitken mode particles, and the ultrafine particles in general, were derived from automotive engine emissions and, to some extent, from oil combustion. The accumulation mode particles remained unchanged in number concentration and daily patterns, and they did not show any dependence on local traffic. This finding indicates that the accumulation mode consisted of regional aerosols.

Since the ventilation air supply into the building operated continuously at a high ventilation rate, we expected the rapid changes in the particle number concentration outdoors to be reflected by the particle number concentration indoors with a short delay. It was also obvious that a steady-state condition for the particle exchange rate was attained between outdoor and indoor air. The I:O ratios for the nucleation mode (<0.6) and Aitken mode (0.6–0.8) were constantly lower than that for the accumulation mode (>0.8); this result agrees with the general statement that particles within the diameter range 0.1–1 μm have the highest penetration factor through mechanical ventilation systems (20).

The I:O ratios for the different particle modes in our study (figure 8) were larger than those in the study of Koponen et al (3). This difference could be partly due to the season of the measurement campaign, as the total number concentration of outdoor aerosol particles was much lower (about half) in summer [this study] than in winter [in the study of Koponen et al (3)]. It should be noted that outdoor conditions, such as air temperature, relative humidity, and pressure vary widely between winter and summer. Therefore, there may be seasonal differences in the I:O ratio due to different meteorological conditions (21, 22).

Another likely reason for the larger I:O ratios observed by us is the filter installed in the mechanical ventilation system, an EU3-class filter in this study and an EU7-class filter in the study of Koponen et al (3). The filtration efficiency of an EU3-class filter is lower than that of an EU7-class filter, and hence higher I:O ratios could be expected in our study, especially for the particle diameter range of 0.1–1.0 μm. Thus a high filtration efficiency filter in the mechanical ventilation system seems to be an important means of producing better indoor-air quality.

In conclusion, the patterns of fine particulate air pollution inside an office room could be largely estimated on the basis of the outdoor aerosol characterization and the mechanical ventilation system. In order to achieve a better understanding of indoor-air quality in relation to outdoor particulate air pollution, we recommend new intense measurement campaigns and controlled studies of longer duration.

Acknowledgments

We thank Sari Yli-Koivisto for her assistance with the measurement campaign, the personnel of the Laboratory of Heating, Ventilation and Air-Condition Technology at the Helsinki University of Technology for the

ventilation rate measurements, Matti Hämäläinen from The Finnish Road Administration for providing the traffic density data, and the Finnish Meteorological Institute for providing the meteorological data of the study period.

This study was funded by the Academy of Finland, Finnish Research Programme on Environmental Health (SYTTY; project number 160639).

References

1. McMurry PH. A review of atmospheric aerosol measurements. Atmos Environ 2000;34:1959–99.
2. Kulmala M, Riihiluoma V, Raunemaa T. Particle emission from gasoline powered vehicles: emission, deposition and re-emission under different traffic density situations. J Aerosol Sci 1986;17:973–83.
3. Koponen IK, Asmi A, Keronen P, Puhto K, Kulmala M. Indoor air measurement campaign in Helsinki, Finland 1999—the effect of outdoor air pollution on indoor air. Atmos Environ 2001;35:1465–77.
4. Sanchez DC, Mason M, Norris C. Methods and characterization of organic emissions from an indoor material. Atmos Environ 1987;21:337–45.
5. Thatcher TL, Layton DW. Deposition, resuspension, and penetration of particles within a residence. Atmos Environ 1995;29:1487–97.
6. Tung TCW, Chao CYH, Burnett J. A methodology to investigate the particulate penetration coefficient through building shell. Atmos Environ 1999;33:881–93.
7. Mosley RB, Greenwell, DJ, Sparks LE, Guo Z, Tucker WG, Fortmann R, et al. Penetration of ambient fine particles into the indoor environment. Aerosol Sci Technol 2001;34:127–36.
8. Jamriska M, Thomas S, Morawska L, Clark BA. Relation between indoor and outdoor exposure to fine particles near a busy arterial road. Indoor Air 1999;9:75–84.
9. Thornburg J, Ensor DS, Rodes CE, Lawless PA, Sparks LE, Mosely RB. Penetration of particles into buildings and associated physical factors. Part I: Model development and computer simulations. Aerosol Sci Technol 2001;34:284–96.
10. Buzorius G, Hämeri K, Pekkanen J, Kulmala M. Spatial variation of aerosol number concentration in Helsinki city. Atmos Environ 1999;33:553–65.
11. Väkevä M, Hämeri K, Kulmala M, Lahdes R, Ruuskanen J, Laitinen T. Street level versus rooftop concentrations of submicron particles and gaseous pollutants in an urban street canyon. Atmos Environ 1999;33:1385–97.
12. Adachi M, Okuyama K, Kousaka Y, Moon SW, Seinfeld J H. Facilitated aerosol sizing using the differential mobility analyser. Aerosol Sci Technol 1990;12:225–39.
13. Jokinen V, Mäkelä JM. Closed-loop arrangement with critical orifice for DMA sheath/excess flow system. J Aerosol Sci 1997;28:643–8.
14. Birmili W, Stratmann F, Wiedensohler A. Design of a DMA-based size spectrometer for large particle size range and stable operation. J Aerosol Sci 1999;30:549–53.
15. Seinfeld HS, Pandis SN. Atmospheric chemistry and physics: from air pollution to climate change. 2nd ed. New York (NY): John Wiley & Sons; 1998.
16. Mäkelä JM, Koponen IK, Aalto P, Kulmala M. One-year data of submicron size modes of tropospheric background aerosol in southern Finland. J Aerosol Sci 2000;31:595–611.
17. Birmili W, Wiedensohler A. New particle formation in the plume of a city. J Aerosol Sci 1997;28:717–8.
18. Harris SJ, Maricq MM. Signature size distributions for diesel and gasoline engine exhaust particulate matter. J Aerosol Sci 2001;32:749–64.
19. Pakkanen TA, Kerminen V-M, Korhonen CH, Hillamo RE, Aarnio P, Koskentalo T, et al. Urban and rural ultrafine (PM0.1) particles in the Helsinki area. Atmos Environ 2001; 35:4593–607.
20. Hinds WC. Aerosol technology. 2nd ed. New York (NY): John Wiley & Sons; 1999.
21. Hussein T, Hämeri K, Kulmala M. Long-term indoor-outdoor aerosol measurement in Helsinki, Finland. Boreal Environ Res 2002;7:141–50.
22. Chan, AT. Indoor-outdoor relationship of particulate matter and nitrogen oxides under different outdoor meteorological conditions. Atmos Environ 2002;36:1543–51.