INDOOR AND OUTDOOR PARTICLE MEASUREMENTS IN A STREET CANYON IN COPENHAGEN

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ABSTRACT
Particle number concentrations and size distributions were measured in the living room of an unoccupied apartment located in a street canyon in central Copenhagen, in the street, and at a nearby urban background station. A simple dispersion model was used to calculate the particle concentrations outside a window facing the street from where most of the ventilation air was supplied. The penetration efficiencies and the deposition rates were estimated using the concentration rate balance, ignoring indoor sources.

The analysis indicates that the deposition rate of particles in the apartment is negligible for PM₁₀ and for particles in the size range 100 - 700 nm. In the size range below 100 nm the deposition rate increases with decreasing particle diameter to a value of approximately 1 h⁻¹ at 10 nm. The penetration efficiency shows a maximum of 60% at 100 nm. The penetration rate for PM₁₀ was found to be 43%.

INDEX TERMS
Indoor traffic particles, Indoor PM₁₀, Penetration efficiency, Deposition rate.

INTRODUCTION
Several institutions in the Copenhagen region have initiated a collaboration on the study of the indoor-outdoor relation of particles from traffic. The objective of the work is to develop and validate a model capable of predicting indoor particle pollution from traffic, based on information about outdoor particle pollution together with construction details of the building envelope and the ventilation system. The relationship will be obtained for different particle size fractions. The model will be developed by analysis of data obtained from outdoor and indoor monitoring of concentrations together with information about the air exchange rate. Methods and some preliminary results are presented.

METHODS
The apartment used in the present study is located in a residential building in a street canyon, Jagtvej, in central Copenhagen, Denmark. The uninhabited, but fully furnished, apartment is on the fourth floor of a five-floor building, approximately 300 m from an existing monitoring station on the other side of the street. The kitchen was used for most of the instruments during the first 5 weeks measuring campaign in May-June 2001. The kitchen was sealed from the rest of the apartment by an airtight door with holes for the tubes and the wires connecting the instruments in the kitchen with the sampling points and the sampling devices in the apartment. The floor space of the apartment, excluding the kitchen, is approximately 30 m².

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The sampling was performed near the midpoint of the living room and right outside a window of the living room facing the street. Most of the ventilation air was supplied via a 10 cm$^2$ opening in this window. A mechanical exhaust system is installed with an exhaust opening in the bathroom. This is the dominant exit route of ventilation air. The air exchange rate of approximately 0.8 h$^{-1}$ in the daytime is reduced to approximate 0.4 h$^{-1}$ during late night and early morning (h = 3600 s). Outdoor measurements have been provided from the routine monitoring of street level air quality at Jagtvej, Copenhagen, and the air quality and meteorological observations from an urban background station located on the roof of the H.C. Ørsted Institute, University of Copenhagen.

A variety of instruments and techniques is used, for example scanners of particle number concentrations and size distributions (DMA), Aerosol Particle Sizer (APS), PM$_{10}$ monitors (TEOM), monitors for nitrogen oxides (NO$_x$), ozone and carbon monoxide, cascade impactors (BLPI and MOUDI), and constant concentration tracer gas technique for the air exchange rate. For the comparison, all data with high time resolution are averaged on a half-hour basis. The PM$_{10}$ measured by the TEOM monitors was collected at a temperature of 50°C.

Half-hour averages of particle number concentrations and size distributions were measured in the living room, at the street station (JGTV), and at the urban background station (HCOE). Particles outside the window of the living room (JGTV83_EXT) were not measured directly. Instead, using a simple model, the particle concentrations were calculated on the basis of measured NO$_x$ half-hour concentrations outside the window, in the street, and in the urban background. The air outside the window is considered as a mix of the background air and of the air at the street station corrected for background contributions:

\[
[\text{Particles}]_{\text{JGTV}83_{-}\text{EXT}} \approx [\text{Particles}]_{\text{HCOE}} + \alpha ([\text{Particles}]_{\text{JGTV}} - [\text{Particles}]_{\text{HCOE}}),
\]

where

\[
\alpha = \frac{[\text{NO}_x]_{\text{JGTV}83_{-}\text{EXT}} - [\text{NO}_x]_{\text{HCOE}}}{[\text{NO}_x]_{\text{JGTV}} - [\text{NO}_x]_{\text{HCOE}}}. 
\]

The variable $\alpha$ is a measure of the relative contribution of traffic polluted air from the street canyon. The apartment is in the lee side of the street relative to the predominant westerly wind direction, while the street station is in the wind side. For that reason the NO$_x$ concentration outside the window was in most cases higher than the concentration at the street station ($\alpha > 1$). The transformation of the particle counts from the street station to the point outside the apartment relies on the good correlation between traffic generated particles and NO$_x$ ($r^2 > 0.70$ in the range 19-230 nm), and the fact that the same traffic is passing the two points.

In cases with low NO$_x$ concentrations measured at the street station ($[\text{NO}_x]_{\text{JGTV}} - [\text{NO}_x]_{\text{HCOE}} < 25$ ppb, ppb = $10^{-9}$ mol/mol) an even simpler model is used:

\[
[\text{Particles}]_{\text{JGTV}83_{-}\text{EXT}} \approx [\text{Particles}]_{\text{HCOE}} + \beta ([\text{NO}_x]_{\text{JGTV}83_{-}\text{EXT}} - [\text{NO}_x]_{\text{HCOE}}),
\]

where the coefficient
\[
\beta = \frac{[\text{Particles}]_{JGV} - [\text{Particles}]_{HCOE}}{[\text{NO}_x]_{JGV} - [\text{NO}_x]_{HCOE}},
\]

is used as a constant factor (the average particle/NO\textsubscript{x} traffic emission ratio). Eq. (3) is essentially the same as eq. (1), but in the simplified model the factor $\beta$ is determined by regression analysis using the data of all half-hour occasions. The particle concentrations are measured as a derived function of the diameter, dN/dlog\textsubscript{d} (number concentration per decade of particle diameter). The corresponding derived $\beta$-function is shown in Figure 1. The error bars indicate the standard deviation due to scatter, determined by the regression analysis.

**Figure 1.** Average particle/NO\textsubscript{x} traffic emission ratios ($\beta$) determined for Jagtvej in Copenhagen by regression analysis. The average NO\textsubscript{x} concentrations during the measuring campaign were 39 ppb at the street station, 11 ppb at the urban background station, and 50 ppb outside the apartment window (ppb = 10\textsuperscript{-9} mol/mol).

The PM\textsubscript{10}/NO\textsubscript{x} traffic emission ratio was estimated by regression analysis of the PM\textsubscript{10} and the NO\textsubscript{x} data from the street station. A PM\textsubscript{10}/NO\textsubscript{x} slope of 0.176±0.004 µgm\textsuperscript{-3}/ppb was found. The PM\textsubscript{10} scatter around the regression line was apparently independent of the NO\textsubscript{x} level (due to long range contributions and other non-correlating sources). The PM\textsubscript{10} interception value of the regression line was found to be 11.2±0.2 µgm\textsuperscript{-3}. The PM\textsubscript{10} outside the window was estimated, using the PM\textsubscript{10} measured at the street station plus an additional amount calculated as the product of the PM\textsubscript{10}/NO\textsubscript{x} traffic emission ratio and the measured NO\textsubscript{x} concentration difference between the street and the point outside the window.

The penetration efficiency ($P$) and the deposition rate ($k$) can be estimated from the concentration rate ($CR$) balance using the measured values of the indoor particle concentration ($C$), the outdoor particle concentration ($C_0$), calculated by eq. (1) and eq. (2), or eq. (3) and eq. (4), and the air exchange rate ($a$):

\[
CR_{\text{source}} = CR_{\text{sink}}, \quad \text{or}
\]

\[
PaC_0 = \frac{dC}{dt} + aC + kC,
\]

where indoor sources are ignored.
The result of the fit for a single size channel, representative for the traffic generated particles, is shown in Figure 2. To reduce the influence of outliers, a special fitting technique has been applied (see Figure 3), using percentiles of the normalised differences between the right side and the left side of eq. (5).

![Figure 2](image)

**Figure 2.** The fitted concentration rate balance for the 23 nm particle size channel (Fitted values: $k = 1.07 \text{ h}^{-1}$, $P = 42\%$). The markers indicate two different intervals of air exchange rate.

![Figure 3](image)

**Figure 3.** The fitting principle: Percentile distributions of the normalised difference between the two equated terms in the concentration rate balance (eq. (5)) are calculated. The fitting by adjustment of $k$ and $P$ searches for a zero point at the position where the slopes of the (smoothed) distributions are steepest for 2 representative intervals of air exchange rates.
RESULTS AND DISCUSSION
The results for particle sizes > 10 nm are shown in Figure 4. The analysis indicates that the deposition rate of particles in the apartment is < 0.1 h\(^{-1}\) in the particle size range > 100 nm (some values turned out as slightly negative). In the size range < 100 nm the deposition rate increases with decreasing particle diameter to a value of approximately 1 h\(^{-1}\) at 10 nm.

![Graph showing deposition rate and penetration efficiency against particle diameter.](image)

**Figure 4.** Penetration efficiencies and deposition rates calculated by fitting the concentration rate balance.

This is an order of magnitude higher than expected in a theoretical study for smooth indoor surfaces and comparable room dimensions (Lai and Nazaroff, 2000). The reason for this may be the occurrence of furniture and textile surfaces in the living room, combined with some stirring of the air performed by a small fan placed in the living room. The penetration efficiency has a maximum of 60% near 100 nm. The results show some agreement with night-time values found in an experimental study conducted in nine non-smoking homes in the Boston area (Long et al., 2001). In that study the calculated deposition rate increases gradually with decreasing particle size from approximately 0.1 h\(^{-1}\) at 400 nm to approximately 0.4 h\(^{-1}\) at 20 nm.

For PM\(_{10}\) a penetration efficiency of 43 % and a deposition rate of zero was found using the same method of calculation.

On some evenings and nights were observed episodes of increased indoor concentrations of PM\(_{10}\) and particles in the size range > 100 nm, which could not be related to increased outdoor concentrations. We believe that these episodes are due to penetration from the underneath apartment (maybe in connection with extraordinary party events). The method used in the study sort these data out as outliers.
CONCLUSION AND IMPLICATIONS
The results are only preliminary. The method will be improved in the next campaign by including particle measurements just outside the living room window. In addition, direct measurements of the penetration efficiency will be performed by initial cleaning of the indoor air for particles, using high-volume absolute filtration inside the apartment.

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REFERENCES