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Quantification of ultrafine particles from second-hand tobacco smoke infiltration

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SUMMARY

This paper presents some of the results of a second-hand tobacco smoke intervention study carried out in 19 flats in four different buildings. Two of the investigated buildings were non-renovated and two others were renovated. The aim of the study was to quantify infiltration of ultrafine particles from a smoker's flat into a non-smoker's flat. In addition, several tests were carried out to describe some solutions for reduction of particle concentrations in the smoker's flat and the non-smoker's flat. The air change rates and the indoor particle concentrations were measured continuously during the measuring periods. The particle sources (particle generating activities) were cigarette-burning in the un-occupied buildings and candle-burning in the occupied buildings. Reductions of the concentration of ultrafine particles using air cleaning devices were studied. Results showed that the transfer of ultrafine particles was about 9% when the source flat was located below the receiving flat, whereas the transfer was 1-2% when the source flat was on the same floor as, or above, the receiving flat.

INTRODUCTION

Second-hand tobacco smoke (SHS) in flats is an emerging public issue in the Nordic countries, in particular in Denmark, where people spend approx. 16 h/day indoors [1]. Smoke can infiltrate a flat in various ways. The infiltration rate depends on the tightness of the building envelope and its design. A Danish study shows that window slits only replace 14% of the exhausted air; the rest comes from elsewhere in the building [2]. Some of the common openings where smoke seeps from a smoker's flat into a non-smoker's flat include electrical outlets, cable or phone jacks, pipes (plumbing), cracks in walls and floors, etc.

Numerous studies have documented the contribution of tobacco smoke to elevate the concentration of ultrafine and fine particles indoors [3]. During recent years investigations have indicated a possible association between exposure to ultrafine particles and human health [4].

Several studies show that the concentration of particles indoors may be reduced to a certain extent by means of ventilation or by filtration using portable or in-duct air cleaners [5]. However, the ventilation rate in residential buildings is generally not designed to remove particles and gases originating from smoking.

Most previous studies have focused on the quantification of particles from direct exposure to SHS. However, very few studies have examined quantification of particles from indirect exposure to SHS. Therefore the aim of the present study is quantification of ultrafine particles (UFP) from SHS infiltration in flats.

METHOD

The study was carried out in four different residential buildings. Two of the buildings (Buildings A and B) are of exactly the same type and design, they are approx. 70 years old and not renovated. The third building (Building C) is 100 years old and recently partially renovated, whereas the fourth building (Building D) is 140 years old and recently completely renovated. Four flats were included in the study in Building A and two flats in Buildings B, C and D, respectively. In each building the studied flat (Flat 2) was placed immediately above another flat (Flat 1).

Figure 1 illustrates a complete unit of flats for the present study. In Building A a complete unit was used. In Buildings B, C and D Flat 1 and Flat 2 were used.

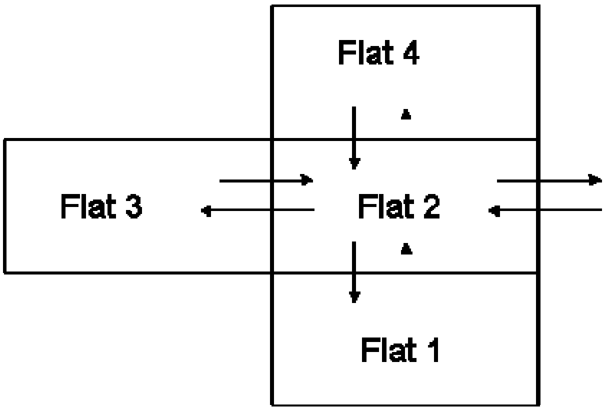

Figure 1. Sketch of a complete unit of flats.

Particles were generated in one flat and the infiltration of UFPs was measured in the flat above. The particle sources (particle generating activities) used in the source flats (Flat 1) was cigarette-burning in the un-occupied buildings (Buildings A) and candle-burning in the occupied buildings (Building C and D). Building B was an un-occupied building, which was used in both cases, i.e. cigarette-burning and candle-burning. Two cigarettes were burned for approx. 10 minutes each in the un-occupied flats and three pure wax candles were burned in the occupied flats.

The UFP concentrations were monitored by means of three condensation particle counters. One of the particle counters was placed in the source flat (Flat 1, where particles were generated), the second one in the exposure flat (Flat 2, which was infiltrated by particles from Flat 1) and the last one was used for sampling the outdoor concentration. Two of the particle counters were TSI model P-Trak 8025. The third one was a TSI model CPC 3007, which was used for measurements in the outdoor air.

The P-Trak 8525 instrument enabled real-time measurement of particle number concentration and data collection. The particle detection range of the instrument was between 0.02 and about 1.0 µm. The CPC 3007 was similar to the P-Trak 8525 with data recording in the diameter range from 0.01 to about 1 µm [6].

The PFT technique (Per Fluorocarbon Tracer) was used to measure air change rates, air infiltration and air exfiltration in the apartments. The technique is a multiple tracer-gas method based on passive sampling. CO_2, temperature and relative humidity were recorded during the experiments. Possible solutions, such as placement of one or two electrostatic air cleaners (AC; CADR=240m^3/h), were investigated for reduction of exposure concentration in Flat 1 and Flat 2.

RESULTS

Figure 2 illustrates an example of the measured concentration course for tobacco smoke in Flat 1 (source flat) and in Flat 2 (exposure flat). Two cigarettes were burned in Flat 1, one in the living room and one in the bedroom. Background concentration in Flat 2 was approx. 4.0E+09 p/m^3 during the night of the measurement.

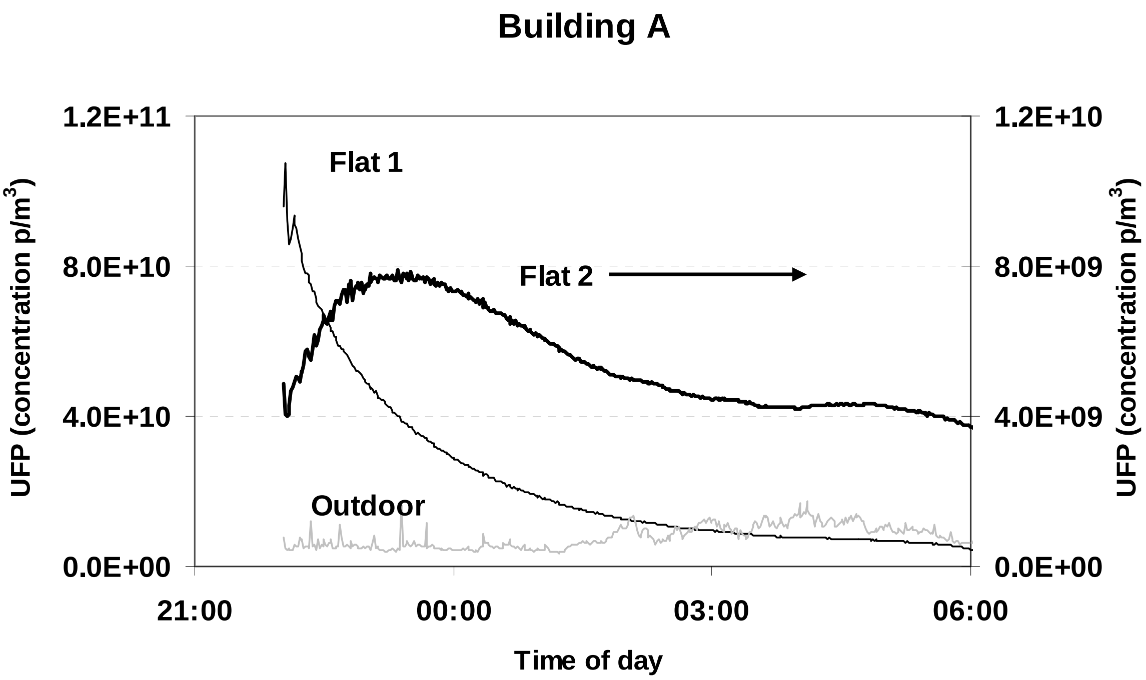

Figure 2. Measured concentration of UFP in Flats 1 and 2 and outdoors at Building A.

Figure 3 illustrates measured and calculated concentration of UFP in the exposure flat (Flat 2) in Building A. A mass balance model, previously applied to analysis of gaseous contaminant concentrations was used [7]. The basic assumptions that govern the model are that particles are perfectly mixed within Flat 2, i.e. the concentrations of particles are uniform throughout the whole volume.

$$c_{r(t)} = \frac{c_s \dot{V}}{\dot{V}+rV} + \frac{\dot{M}}{\dot{V}+rV} - \frac{\dot{V}}{\dot{V}+rV}\left[c_s + \frac{\dot{M}}{\dot{V}} - \frac{\dot{V}+rV}{\dot{V}} c_{r(0)}\right] e^{-\left[\frac{\dot{V}}{V}+r\right]\tau} \qquad (1)$$

Where $\dot{V}$ = air flow rate (m^3/h), c_s = supply air concentration of UFP (p/m^3), c_r = air concentration of UFP in flat (p/m^3), V = flat volume (m^3), r =particle removal rate (1/h). $\dot{M}$ =

particle transfer from Flat 1 to Flat 2 ((p/m^3)*(m^3/h). $\dot{M}$ was estimated by multiplying the UFP concentration in Flat 1 (the source flat) by the air leakage from Flat 1 to Flat 2.

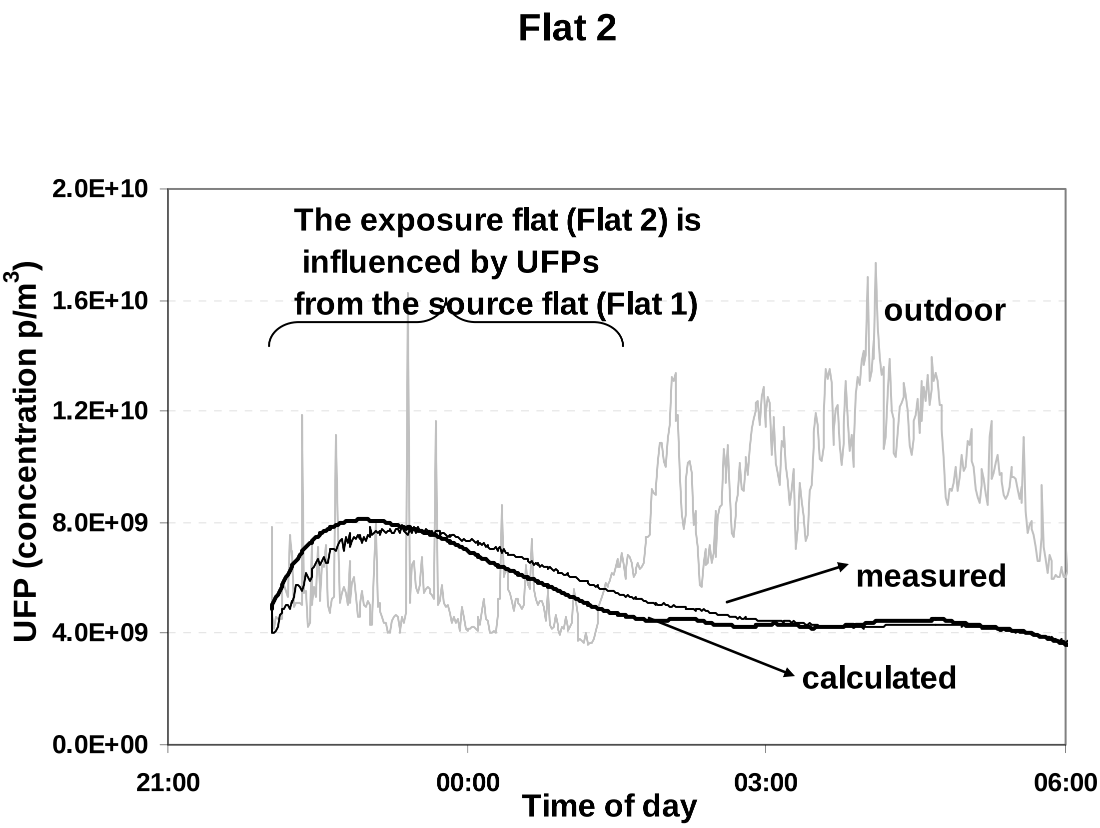

Figure 3. Results of measured and calculated of concentration of UFP in Flats 1 and 2 in Building A.

Tables 1 to 2 show the measured and calculated parameters of tobacco smoke in the exposure flat (Flat 2) in the Buildings A. Table 3 shows measured and calculated parameters for experiments with burning candles in Building B, C and D. It should be noted that Building B was a non-renovated building of exactly the same kind as Building A. Building C was recently partially renovated and Building D was recently completely renovated.

The second column in Tables 1 and 3 show the relative exposure in Flat 2, which means the percentage of UFP generated in Flat 1 that infiltrates Flat 2. The exposures in Flat 2 in Table 2 comprise infiltration inclusive reduction because of operation of the air cleaning devices.

The relative exposures in Flat 2 were obtained by expressing the total number of tobacco-related particles or candle related particles in Flat 2 as a percentage of the total number of particles measured in Flat 1 including background concentration. The total number of tobacco-related particles (or candle related particles) in Flat 2 was assessed as the area between two concentration curves calculated using equation 1. The first curve was calculated with consideration of particle transport by air leakage from Flat 1 to Flat 2. The second curve was calculated with the air leakage set to zero. Thus, the difference between these curves is an estimate of the particle transport from Flat 1 to Flat 2.

The third column shows removal rates of UFP in Flat 2. The removal rates are the sum of the deposition of particles on the inner surfaces of the rooms, removal by ventilation, and other sink mechanisms. The fourth column shows the air change rate in the Flat 2. The fifth column shows the air transfer due to leakage from Flat 1 to Flat 2. The air change rates and air transfer were set at weak mean values.

The rows 2 to 4 in Table 1 show data for successive experiments in Building A, where sources were placed in Flats 1, 4 and 3 respectively.

Table 1. Measured and calculated parameters of tobacco smoke in Flat 2 in Building A.

	Relative exposure(infiltration) in Flat 2 (%)	Removal of UFP in Flat 2 (1/h)	Air change rate in Flat 2 (1/h)	Leakage (m^3/h)
From Flat 1 to Flat 2	8.6	0.9	0.41	14
From Flat 4 to Flat 2	1.8	1.5	0.41	5
From Flat 3 to Flat 2	1.1	1.4	0.41	5

Another aim of the study was to describe to what extent air cleaner devices and the different states of renovation of buildings would affect the transfer of UFP between two flats.

Table 2 shows measured and calculated parameters of tobacco smoke in Flat 2 in Building A. The experiments were carried out in Flat 1 and Flat 2 in Building A. Colum 1 in Table 2 shows the location and number of air cleaners (AC) operated in Flat 1 and Flat 2.

Table 2. Measured and calculated parameters tobacco smoke in Flat 2 in Building A. With air cleaner (AC).

	Relative exposure (infiltration incl. reduction by AC operation)* (%)	Removal of UFP in Flat 2 (1/h)	Air change rate in Flat 2 (1/h)	Leakage (m^3/h)
From Flat 1 to Flat 2 1 AC in Flat 1	5.0	1.0	0.41	15
From Flat 1 to Flat 2 1 AC in Flat 2	4.2	1.9	0.41	15
From Flat 1 to Flat 2 2 ACs in Flat 2	2.6	3.9	0.41	16

Table 3 shows that the test with burning candles gave a relative exposure of 2.6% in Building B. This is about 1/3 of the value obtained with tobacco smoke in Building B, which gave a relative exposure of 7.1%. However, the tests with tobacco smoke in Building A and Building B showed similar results, see Table 1.

Table 3. Measured and calculated parameters of burned candles in Flat 2 in Building B, C and D.

	Relative exposure(infiltration) in Flat 2 (%)	Removal of UFP in Flat 2 (1/h)	Air change rate in Flat 2 (1/h)	Leakage (m^3/h)
From Flat 1 to Flat 2 Building B	2.6	2.7	0.74	10

From Flat 4 to Flat 2 Building C	0.3	4.4	0.92	2.3
From Flat 3 to Flat 2 Building D	0.7	1.5	0.36	5

DISCUSSION

There are various ways that smoke infiltrates from one flat to another. The air infiltration rate between two flats depends on the age, construction and tightness of the flat after renovation. A leaky flat exposes its occupants to pollution from surrounding flats, especially adjacent ones, and especially from smokers living in a flat below.

The results from the experiments in the two non-renovated buildings, A and B, indicated that 7-9% of the amount of UFP, generated by tobacco smoke in the source flat (Flat 1), infiltrated the flat located above (Flat 2), see Table 1.

The measurements with candle-burning in Building B, under the same test conditions as the tobacco smoke experiments, indicated an infiltration of 2-3% of UFP from Flat 1 to Flat 2, see Table 3. The difference in the infiltration rate of UFP has not been clarified but might depend on different characteristics of the particles generated by tobacco smoking compared with candle-burning.

It should be noted that the background concentration of UFP was 4.0E+09 p/m^3 during night time while it increased to approx. the double during day time.

The results from the example case (see Figures 1 and 2) showed that two cigarettes generated a mean value concentration of 2.2E+10 p/m^3 with a maximum concentration of 9.6E+10 p/m^3 in the source flat (Flat 1). The maximum concentration in the exposure flat (Flat 2) was somewhat less than 1/10 of that in Flat 1. The concentration declined to the background concentration after approx. 3 hours. Thus, occupants were exposed to a higher particle concentration compared with the background concentration during several hours.

Table 3 showed that the infiltration from the source flat (Flat 1) to the exposure flat (Flat 2) was lower in the renovated buildings, i.e. Buildings C and D compared with Buildings A and B which were non-renovated.

Technical solutions

The concentration of UFP in the exposure flat can be reduced by three different control methods; source control, ventilation control and use of portable air cleaning devices.

Source control: A smoke-free residential building is one of the remedial solutions suggested to private building owners, and it is known in several countries, including Sweden, Canada, USA and Norway.

In order to implement smoke-free residential buildings in public residential buildings, it is required to change the law or grant exemptions by the authorities. According to the law in Denmark, it is allowed to smoke tobacco in private homes.

Another method for reducing exposure to neighbour smoke is efficient sealing of the leaks in electrical outlets, cable or phone jacks, pipes (plumbing), cracks in walls and floors, etc. On the other hand different types of building construction and different types of leaks and cracks require different sealing methods. The results in the present paper shows that renovation of the buildings reduced the infiltration of UFP from the source flat to the exposure flat, see Table 3. However, the project also aims to study more in detail the sealing-effect on the transfer of tobacco smoke between two flats. This part will be carried out during the winter of 2010.

Ventilation control: Ventilation reduces the concentration of pollutants by means of dilution in order to ensure an adequate indoor air quality. Generally, the air in a flat should be supplied to the bedrooms and living rooms and exhaust should take place from the bathrooms and kitchen. In a non-renovated building, like Building A, the ventilation system was natural i.e. there was no fan to exhaust the particles from the flats. The amount of air that enters a building with natural ventilation depends on the wind and the thermal effects occurring within the building. The air change rate in Building A was 0.41 h^{-1} and in Building B 0.74 h^{-1}. This project also aims to find the ventilation effect on the transfer of the tobacco smoke between two flats. This part will be carried out during the winter of 2010.

Portable air cleaning devices: Portable room air cleaners can be used to clean the air in a polluted room when continuous and localised air cleaning is needed. For air cleaning devices to be effective, the capacity of the air cleaner must match the ventilation rate of the room. This cleaning technology is useful when there is no opportunity to clean the supply air by filtration, i.e. buildings with a natural ventilation system or with an exhaust ventilation system. Consumers should also consider possible side effects such as noise and ozone generation, when considering using air cleaning devices.

Measurement and calculation in Building A showed that, when one air cleaner was placed in the source flat, the relative exposure in the exposure flat (receiving flat) was reduced from 8.6% (without air cleaner) to 5% (with air cleaner). However, operating an air cleaner in the source flat will reduce the exposure in the source flat, and the exposure in the receiving flat can be expected to decrease accordingly. Thus, it was expected that the relative exposure (the ratio of the exposure increase in the receiving flat to the exposure in the source flat) should remain unchanged. The reason for the deviation has not been clarified. However, when using an air cleaner in the source flat the concentration varied rapidly. The peak concentration was reached after 9 minutes and decreased to 10% of the peak concentration within 1.4 h. Without an air cleaner in the source flat the concentration changed more slowly; the concentration decay to 10% of the peak value lasted about 5 h. It is not likely that the particles will have had the time to spread well between the rooms in the source flat so probably, when using an air cleaner in the source flat the source is mainly limited to one room. The measurement may therefore have lead to an overestimation of the exposure in the source flat, since the concentration was measured in the same room as where the tobacco smoke was generated. An overestimation of the exposure in the source flat will lead to an underestimation of the relative exposure in the receiving flat. In the case without air cleaner the measured particle concentration probably reflected the average concentration in the source flat more accurately, due to the much slower concentration changes.

When two air cleaners were placed in the exposure flat, a double removal of the UFP was recorded. However, theoretically, the marginal effect of the second air cleaner should be less than observed, a factor of around 1.5 rather than 2. The deviation between theory and measurements may partly depend on a change of the ventilation rate between the measurement series.

CONCLUSIONS

The results indicated that:

- In the non-renovated buildings between 1% and 9% of the UFPs generated by tobacco smoking infiltrated to a neighbouring flat.
- The transfer (infiltration) was highest (about 9%) when the source flat was located below the receiving flat.
- The transfer was less (1-2%) when the source flat was on the same floor as, or above, the receiving flat.
- The UFP-transfer was lower in the renovated buildings than in the non-renovated buildings.
- When one air cleaner was used in the receiving flat in one of the non-renovated buildings, the exposure to the neighbour's tobacco smoke decreased from 9% to 4%. When using two air cleaners the exposure decreased further down to less than 3%.

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