TRANSFER OF ULTRAFINE PARTICLES AND AIR IN MULTI-STOREY BUILDINGS

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ABSTRACT
An emerging issue in Denmark is passive smoking in residential buildings where non-smokers are exposed to harmful smoke from their neighbours. There are various ways that smoke infiltrates from one flat to another. The air infiltration rate between two flats in a multi-storey building depends on its construction, tightness and age.
This paper presents some of the results from of a study with transfer of ultrafine particles and tracer gas carried out in an older multi-storey building in Copenhagen. The aim of the study was to quantify the transfer of ultrafine particles and gases from one flat to another flat before and after sealing of the floor. The floor between the two flats was sealed using a new floor sealing method. The sealing method is developed by a specialist firm in sealing.
Indoor ultrafine particle concentrations and tracer gas were measured continuously in the two flats during the measuring periods. The gas source was N_2O and the particle source was burning cigarettes in the unoccupied flat. Reduction of the concentration of ultrafine particles and gases by sealing the floor with polyethylene and joint filler of bitumen was studied.
It was evaluated how the sealing performed with regard to decreasing the amount of transferred ultrafine particles and a tracer gas between two flats separated by a floor. When the floor between the flats was not sealed, the results showed that the transfer of ultrafine particles was about 4% and the transfer of tracer gas was 14%. After sealing, the transfer was reduced to 1.6% and 5% respectively.

Keywords
Particles, Air pollution, Ventilation, Full-scale experiments

INTRODUCTION
In multi-storey buildings, it can happen that residents are exposed to polluted air from the surrounding flats. The polluted air is usually associated with odour from activities as cooking and / or tobacco smoke. Tobacco smoke is harmful and therefore technical solutions needs to be developed to reduce the transmission of ultrafine particles in multi-storey buildings.
To what extent air pollution – airborne particles – is transferred from one flat to another depends on the construction of the building, the age of the building, density and the ventilation system. In an earlier study (1), the transfer of ultrafine particles from one flat (source flat) to another (exposed flat) was studied. The study showed, among other things, that approx. 9% of the particles from tobacco smoke were transferred when the exposed flat was directly above the source flat.
Previous research studied three technical solutions to reduce the transmission of ultrafine particles in multi-storey buildings (2). The first study examined sealing of the floor of the exposed flat. The other study examined the use of a novel air cleaning duct (Photochemical Air Purification) and the third examined a portable air cleaner (AC).

The first technical solution was tested in a flat in a multi-storey building from the 1930s. Cardboard and plastic foil of polyethylene were used for sealing the whole existing wooden floor in the exposed flat. After the sealing, the results of the study showed that the concentration in the exposed flat was independent of the generation of particles in the source flat.
The second solution was examined in a laboratory environment. The efficiency of the novel air circulating ductwork was examined by investigating the removal of ultrafine particles from a lit cigarette. The test showed that the removal efficiency ranged from 30% and 60% after 10 minutes, i.e. when the cigarette had burned out.
The third solution with a portable air purifier (AC) was investigated in a flat of 110 m2. Here, the efficiency of an air cleaner was studied in relation to the reduction of ultrafine particles from tobacco smoke. By use of an air purifier with a CADR (clean air delivery rate) of 240 m^3/h, the effectiveness of the air purifier ranged from 65% to 75% depending on its location in the flat in relation to the location of the particle generation (3).
Older multi-storey buildings often have leakages where particles can get through. There are leakages from piping in the floor and along the walls. Studies show that particles are not only transferred by the floor but also along the stairwell (1).

METHODS

The study was carried out in a block of flats from 1881. The exposed flat was directly above the source flat. The experiments were performed in January and February 2012. During measurements, no indoor activities took place - i.e. no cooking, cleaning or other activities that could generate particles.

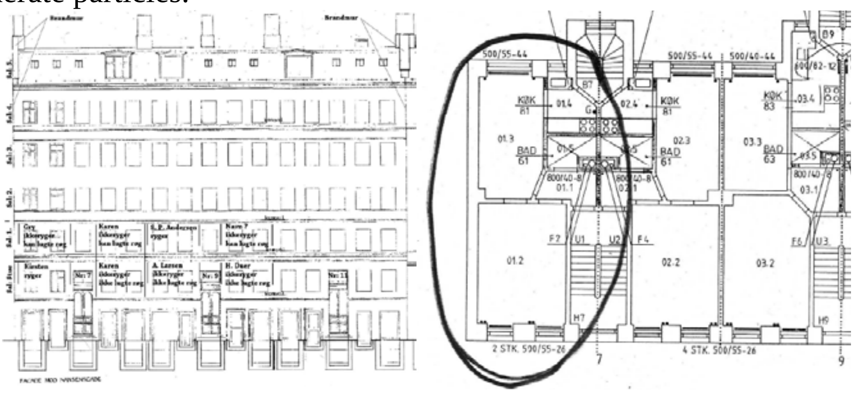

Figure 1: Facade and floor plan of the flats

Figure 1 shows the façade and floor plan of the two flats. The exposed flat and the source flat are laid out the same way. The volume of the flats is approximately 120 m^3. The flats consisted of a living room facing a busy road, a room and a kitchen facing a courtyard, a combined toilet/bath and an entrance in the middle of the flat. The floor of the flats was a lacquered wooden floor in the living room, the room and the hallway. The kitchen had vinyl flooring and the bathroom floor was covered with tiles. The kitchen had cabinets along the inner wall and a sink under the window. The living room and the room had skirting board along the walls and the ceiling had mouldings. In the middle of the ceiling in the living room and in the room was a rosette with a power outlet. Under each window in the living room and the room was a radiator with a heat pipe leading through the floor. There was ventilation in the toilet/bathroom. There was fresh air vents in all the windows.
With the purpose of creating an overpressure in the source flat compared to the exposed flat a higher temperature in the source flat was established. This was ensured by maintaining the temperature of the source flat at 5°C above the temperature in the exposed flat. During the examination the temperature in the exposed flat was approximately 20°C and the source flat was approx. 25°C.

The source for generation of particles consisted of four lit cigarettes that were placed in the lower flat, two in the living room and two in the room. All cigarettes were simultaneously burned out during a period of 10 minutes. The concentration of ultrafine particles were measured by using two particle counters *NanoTracer PNT 1000* from Philips and one condensation particle counter (*CPC*) model *3007* from TSI Incorporated. The particle counters measured concurrently. The two *NanoTracer PNT 1000* were placed in each of the flats and the *CPC 3007* was placed outside.

Besides particles, the air change rate and the transfer of air between the flats was measured by use of two Multi-Gas monitors, type 1302 from Brüel and Kjær, placed in each of the flats. Temperature and humidity were measured every 5 minutes with TinyTags dataloggers type TGU-4500 from Gemini. During particle generation, complete mixing was achieved by using small fans in the room. In the source flat, a top window in the facade facing the busy road was opened approx. 2 cm. All fresh air vents were also opened and the exhaust in the toilet/bath was closed. In the exposed flat all windows, exterior doors and fresh air vents were closed. In the toilet the exhaust was open.

The first part of the experiment was performed without sealing of the floor in the exposed flat. The second part of the experiment was carried out with sealing of the floor in the exposed flat. When the measurements were started the particle concentration in the flat was almost constant with a background concentration of about 10,000 particles per cm^3 in the source flat and 4000 particles per cm^3 in the exposed flat. The cigarettes were lit in the source flat, two in the room and two in the living room. The cigarettes were extinguished just before they burned out. The measurements continued until the ultrafine particle concentration in the two flats reached almost the initial concentration.

Before the last measurements, the floor in the exposed flat was sealed. The sealing method was developed by a specialist firm in sealing. The company chose to use a sealing of a vapour barrier, Icopal Blackline, made of polyethylene. The vapour barrier was put together by overlapping pieces bonded together with joint filler of bitumen. The vapour barrier was placed along the floor and up the walls, where it was sealed with building sealant approved for indoor use along the skirting boards. At the heating pipes, the vapour barrier was sealed with joint filler of bitumen. It is not included in the study to determine whether the products used contribute to the concentration of particles in the exposed flat.

CALCULATION METHODS

The transfer of ultrafine particles and gas was calculated with a calculation method [1] used in previous experiments with second-hand smoke (1).

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

Where $\dot{V}$ = airflow rate [m^3/h]
$\dot{M}$ = particle transfer from flat 1 to flat 2 [(p/m^3) · (m^3/h)]
c_s = supply air concentration of UFP [p/m^3]
c_r = air concentration of UFP in the flat [p/m^3]
V = volume of the flat [m^3]
r = particle removal rate [h^{-1}].

The air change rate in the two flats was calculated by using the decay method [2].

With the decay method, the air change rate is determined by dosing a tracer gas in the flat. The tracer gas is distributed, so total mixing is guaranteed. After dosing of the tracer gas, the decay rate of the tracer gas is measured over time. The air change rate is calculated by the decay curve.

$$C(t) = C_0 e^{-nt} \quad [2]$$

Where C_0 is the start concentration in ppm
$C(t)$ is the concentration in ppm after t
t is the time in hours
n is the air change rate in h^{-1}

RESULTS

Before sealing

Four cigarettes were lit in the source flat, two in the living room and two in the room. The cigarettes were lit at the same time and extinguished just before they burned out. Figure 2 shows the measured concentrations of ultrafine particles in the source flat and the exposed flat. Before generation of ultrafine particles, the background concentration of ultrafine particles in the source flat was approx. 10,000 particles/cm^3 and in the exposed flat approx. 4000 particles/cm^3. The reason that the background concentration was higher in the source flat was that the resident in the source flat was a smoker and smoked indoors. The particles from the tobacco smoke deposited in materials such as furniture, walls and curtains (4). The maximum concentration of ultrafine particles in the source flat was measured to approx. 650,000 particles/cm^3. In the exposed flat, the maximum concentration of ultrafine particles was measured to approx. 11,000 particles/cm3. Figure 2 shows that the maximum concentration in the exposed flat took place 30 minutes after the cigarettes were extinguished.

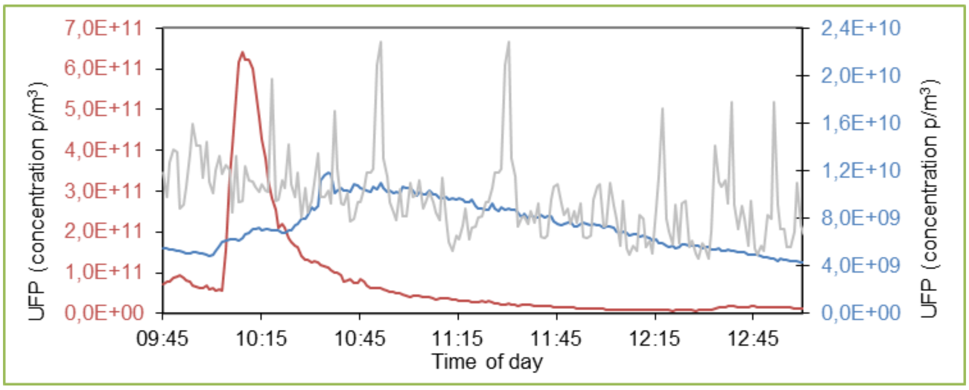

Figure 2: Particle concentration in the flats. Red: The source flat, Blue: The exposed flat, Grey: Outdoor

The transfer of ultrafine particles from the source flat to the exposed flat was found to approximately 4%.

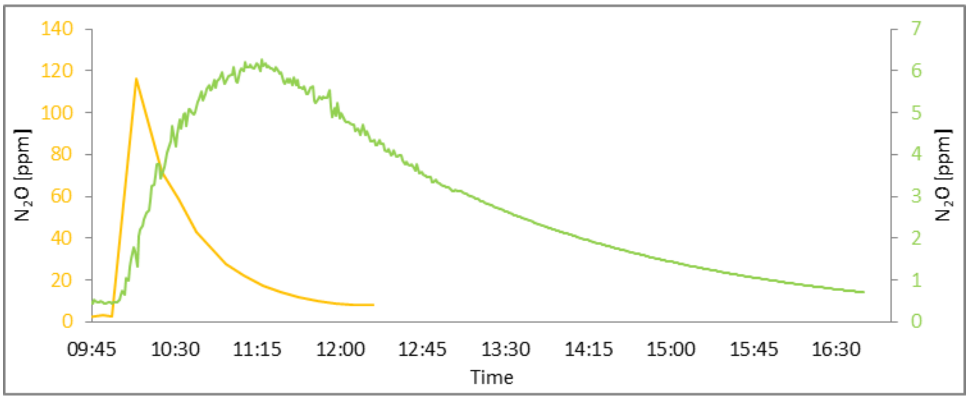

Figure 3: Tracer-gas concentration in the two flats. Yellow: The exposed flat, Green: The source flat

The air change rate in the source flat was calculated to 1.25 h^{-1} and to 0.18 h^{-1} in the exposed flat.

The transfer of tracer gas was calculated to approx. 14%.

After sealing

After the sealing, the particle transfer was reduced from 4% to 1,6% and the transfer of tracer gas was reduced from 14% to 5%. The results showed that sealing more than halves the transfer of particles and tracer gas.

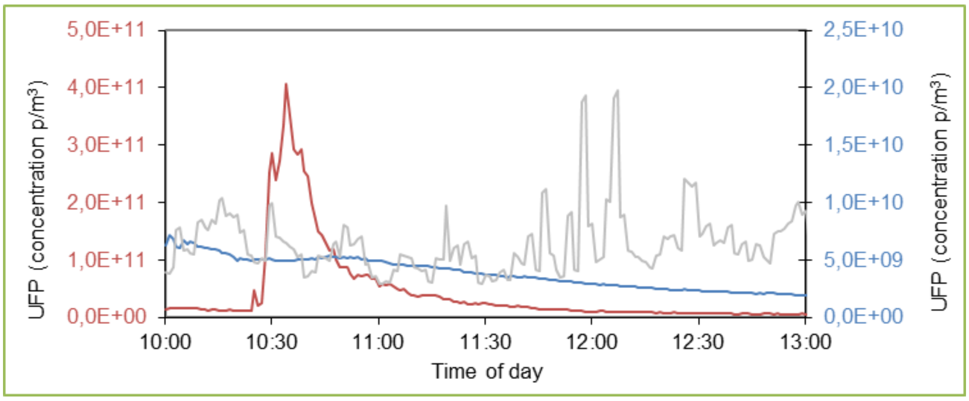

Figure 4: Concentration of ultrafine particles in the flats. Red: The source flat, Blue: The exposed flat, Grey: Outdoor

After the cigarettes were lit in the source flat, the concentration in the exposed flat was at the highest level after approx. 30 min, see Figure 4.

The initial concentration of ultrafine particles in the exposed flat was higher at the beginning of the experiment, than when the cigarettes in the source flat were ignited. This was because the residents were at home right up to the start of the study.

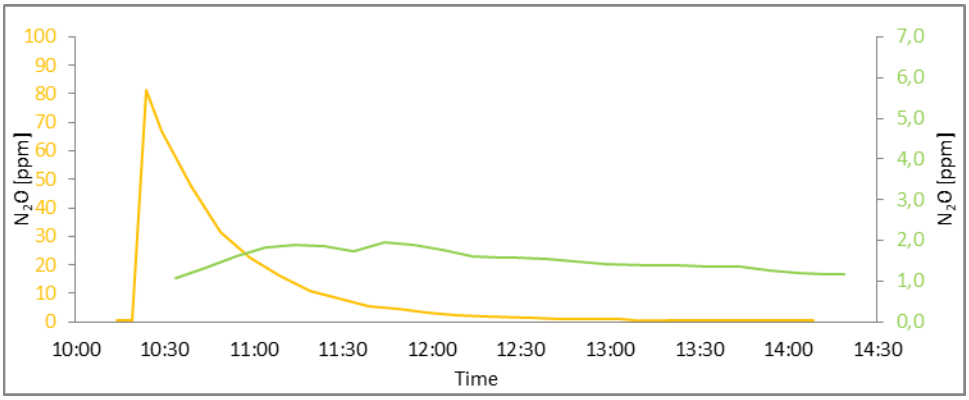

Figure 5: Tracer gas concentration in the two flats. Yellow: source flat, Green: Exposed flat

After sealing of the floor in the exposed flat, the air change rate in the source flat was calculated to be 1.46 h^{-1}. In the exposed flat, the air change rate was calculated to be 0.52 h^{-1}. The air change rate before sealing of the floor was 1.25 h^{-1} and 0.18 h^{-1} respectively. The difference in the air change rate may be due to the fact that when the floor was sealed, a hole was made in the outer wall for a balcony. During the experiment, the hole was sealed with a mattress, but no insulation. Due to the less insulated flat, the infiltration might have had an influence on the air change rate and thereby the air change rate is different. The wind speed for outdoor air was on average 6 m/s and 3 m/s for the two cases respectively (5). This indicated that the wind speed can not explain the increase in the air change rate.
After sealing of the floor of the exposed flat, the transfer of tracer gas from the source flat was calculated to be 5%. Before sealing the floor, the transfer was 14%.

DISCUSSION
In tobacco smoke, there are more than 30 different volatile compounds. The highly volatile compounds deposits on surfaces and in the environment where the pollution occurs (6). Tobacco smoke contains more than 4000 different chemical compounds during combustion (1). During combustion, both gases and particles are emitted. For most people, it is the odour that puts a limit on whether or not to accept tobacco smoke in the indoor environment. The concentration of the particles depends on their volatility (7). The concentration of particles also depends on temperature (increasing degassing with increasing temperature), moisture changes and ventilation (4). Some of the particles deposits on other materials, in particular furry textiles. If for example, the air change rate is low during a weekend, the emitting products deposit in the environment. They do not disappear just because the space is ventilated.

Gas
To investigate the transfer of gases, a tracer gas of N_2O was used. Since there are thousands of different gases consisting of several molecules in a lit cigarette, it is not possible to measure them all, and instead a measurable nitrogen tracer gas was used.
From the investigation, it was found that the transfer of tracer gas was reduced from 14% to 5% after sealing the floor in the exposed flat.
Because the tracer gas was N_2O, the measurements were certain to be only of the tracer gas. But it was uncertain whether it was transferred through the floor or through other leaks in the structure.
Since only a single gas of a specific chemical compound was measured, it is difficult to say how much of the gasses from tobacco smoke can be reduced, when compared with the large amount of different gasses in tobacco smoke.

Particles

The transfer of ultrafine particles was examined by measuring the concentration before and after sealing of the floor. The transfer of ultrafine particles was reduced from 4% to 1,6% after sealing the floor of the exposed flat.

This study showed that the transfer of ultrafine particles was less than the transfer of tracer gas. During the experiments without sealing of the floor, 14% of the tracer gas was transferred while only 4% of the ultrafine particles were transferred. This could be due to the fact that the ultrafine particles deposits on materials such as furniture and walls, and in cracks in the flat. Other factors, such as coagulation, sedimentation, condensation of water vapour on small particles, etc. also play a role.

CONCLUSION

After sealing of the floor in the exposed flat the transfer of ultrafine particle was reduced from 4% to 1,6%. This was more than half of what was transferred before the sealing. Transfer of gases was reduced from a transfer rate of 14% to 5%.

The investigation was performed in an older multi-storey building from the late 1800s. In Copenhagen, there is a great many of this kind of buildings but to verify the study, it is necessary that several different types of multi-storey buildings are tested.

The applied sealing method resulted in a reduction by more than half, of ultrafine particles and tracer gas from the source flat to the exposed flat.

New sealing materials are developed, and there is a need to test them in various types of buildings.

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