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The effectiveness of portable air cleaners against tobacco smoke in multi-zone residential environments

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SUMMARY

The purpose of this study was to investigate how the effectiveness of portable air cleaners (ACs) against tobacco smoke is influenced by the clean air delivery rate (CADR), the location of the AC in relation to the pollution source and the apartment structure. The study was based on field experiments and simulations with the CONTAM software. The AC effectiveness was about 80% for one AC, and 93% for two ACs in the studied apartment (volume=110m³). Ultrafine particles (UFP) exposure in a room without tobacco smoking (clean room) could be much less than in the source room if these rooms were not directly connected with each other (but indirectly connected via doors open to other rooms). Operating the AC in one of the rooms without cigarette smoking could develop a partly isolated clean environment. However, this led to a rather low cleaning effectiveness for the concentration of ultrafine particles in the apartment as a whole. If operating the AC in the room where cigarettes are being smoked, the UFP exposure in the whole apartment can be further reduced.

INTRODUCTION

Environmental tobacco smoke (ETS) exposure relates to an increased risk of many adverse health effects, including lung cancer, asthma onset and exacerbation and acute respiratory illness [1]. In Denmark, about 20% of deaths among adults aged >35 years are due to tobacco smoking [2]. Although tobacco smoking is banned in public places, it appears that children are still at risk of high exposure to secondhand tobacco smoke (SHS) in their home [3, 4]. Therefore, controlling ETS exposure in residential buildings is important to protect smokers' families, especially their children. However, the ventilation rates in residential buildings are generally too small to efficiently remove the tobacco smoking particles (the average air change rate for all studied apartments was 0.48h⁻¹). For residential buildings, especially those with natural ventilation, implementation of room air cleaners may be convenient and effective to control indoor air pollutants. However, the clean air delivery rate of the air cleaners, the relative location of the air cleaner to the pollution source and the apartment structure, as well as the indoor air change rate, all affect the AC effectiveness.

The purpose of this study was to investigate the AC effectiveness against multi-zone tobacco smoke under different CADRs and different locations of the AC. Special attention was paid to the apartment structure and the influence of room dividing doors being open or closed.

METHODS

The field experiments were carried out in an apartment (see Figure 1) with natural ventilation.

The natural ventilation system had air inlets in the living room and bedroom, and air outlet chimneys in the kitchen and WC. The apartment entrance door and all windows were closed during experiments. Indoor and outdoor UFPs concentrations were measured by two condensation particle counters, and temperature and relative humidity were also monitored. A passive tracer gas method was used to measure the air change rate, infiltration from outdoors and air transfer between apartments. Two electrical ACs (each with CADR=240m³/h according to the manufacturer) were used as air cleaning devices. The door between the bedroom and the living room (BL door) and the door to the kitchen (K door) were open or closed during different experiments. The other doors were open during all experiments. The cases of cigarette smoking and AC in the same room and in different rooms, keeping the BL door and K door either opened or closed, or using none, one or two ACs were studied. The AC was started at the same time as smoking started.

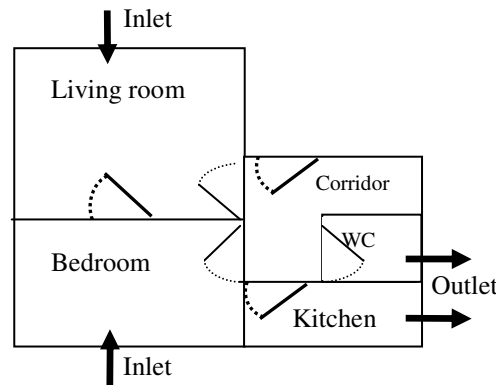


Figure 1. Configuration of the test apartment. The door between the bedroom and the living room is denoted BL door, and the door to the kitchen is denoted K door.

In an apartment, even small temperature differences between rooms can induce large inter-zonal air flows [5], which, furthermore, results in the smoking pollutants being well mixed between the zones. The multi-zone temperature differences were smaller than 2°C in all measured cases. Thus, in the CONTAM simulations the temperature differences (Δt) 0.1°C, 1°C and 2°C were applied according to the following relationship, $t_{\text{bedroom}} = t_{\text{living room}} + \Delta t = t_{\text{corridor}} + 2\Delta t$. The agreement between measurement data and the simulation under the same environmental conditions was tested, and an example, shown in Figure 2, indicated a high degree of agreement between the CONTAM simulation and the measurements.

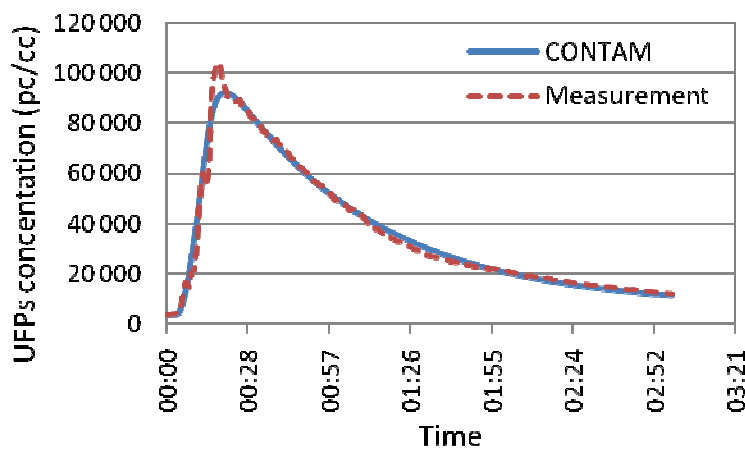


Figure 2. Comparison between CONTAM simulation results and measurement results.

RESULTS

1. Influence of apartment structure on the mixing of indoor particles

Indoor air distribution directly influenced the distribution of tobacco smoking pollutants and the AC effectiveness. Apartment structure, temperature differences between rooms and ventilation can all affect air distribution. Therefore, with the ventilation rate of the apartment kept constant, UFP distribution and AC effectiveness were studied for the following cases: open BL door (directly connecting the “clean” bedroom and the polluted living room - the source room) and closed BL door (the clean bedroom and the living room still being indirectly connected via the corridor), open K door and closed K door (isolating smoke pollutants in the source room – when smoking in the kitchen). CONTAM simulations of the above cases were carried out with multi-zone temperature differences of 0.1°C, 1°C and 2°C, according to the relationship given in the previous section.

1.1 Indoor air well mixed

Figure 3 shows the measured UFP concentrations for the case of keeping the BL door open, smoking 2 cigarettes in the living room and without any AC. The curves of UFP concentration in clean room (bedroom) and source room (living room) almost overlap each other, which mean that keeping the BL door open resulted in well mixed indoor air.

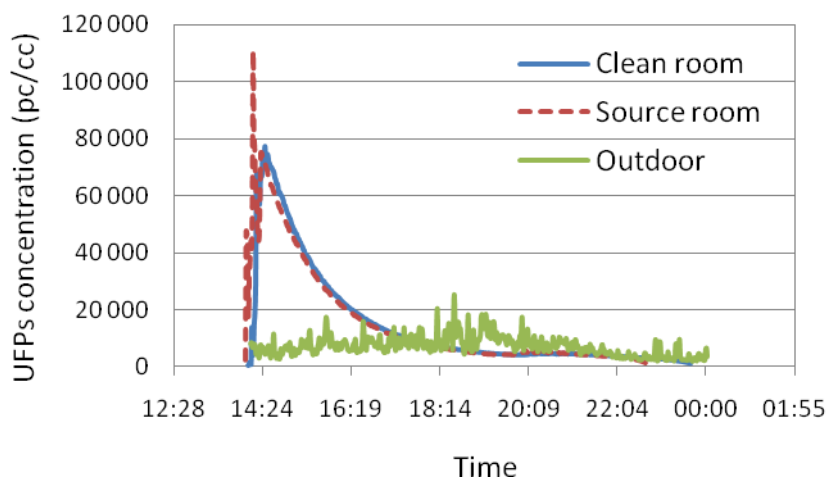


Figure 3. Indoor UFP concentrations for the indoor air well mixed case (BL door open).

1.2 Indoor air not well mixed

The measured UFP concentrations for the case of closed BL door, smoking 2 cigarettes in the living room and without AC in any room are shown in Figure 4. The different peak concentrations and a time delay are obvious between bedroom (clean room) and living room (source room), which means that keeping the BL door closed limited the spread of indoor tobacco smoking pollutants from the source room.

The above results are also shown in Figure 7. UFP exposures were about the same in the living room and in the bedroom if the BL door was open. Otherwise, the UFP exposure was lower in the bedroom than in the living room, when the BL door was closed, as expected.

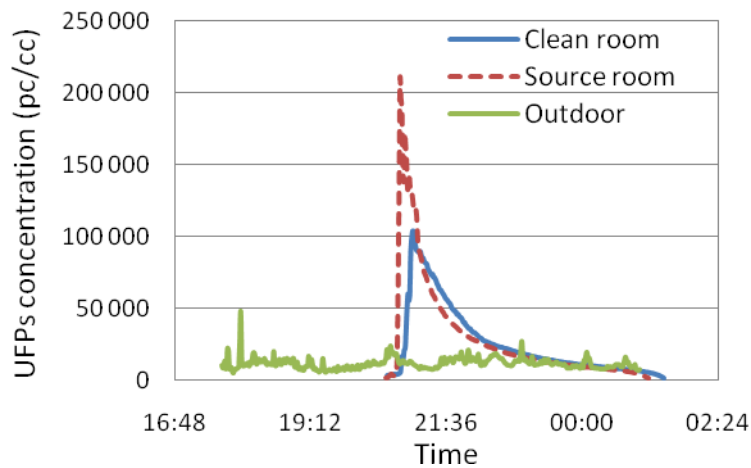


Figure 4. Indoor UFP concentrations for a not well mixed case (BL door closed).

Comparing Figure 3 and Figure 4, it can be seen that keeping the BL door opened or closed clearly influenced the UFP transport from the source room to the clean room. In other words, keeping the BL door closed, to some degree isolated UFPs from the source room to the clean room. The UFP exposure difference (S) between clean room and source room could be defined according to Equation 1, where $E_{\text{cleanroom}}$ is the UFP exposure in the clean room and $E_{\text{sourceroom}}$ is the UFP exposure in the source room.

$$S = 1 - \frac{E_{\text{cleanroom}}}{E_{\text{sourceroom}}} \quad (1)$$

The parameter S represents UFPs exposure isolation between the clean room and the source room. Larger S means that more pollutants are isolated from the clean room. The influence on S by the temperature difference between the rooms was simulated by CONTAM, and the results are shown, together with measurement, data in Figure 5. When the BL-door was closed, but the clean room and the source room indirectly connected, via open doors to the corridor, the UFP exposure could be somewhat less in the clean room than in the source room. The CONTAM simulations showed that, depending on the temperature difference, the exposure difference varied from 38% to 10% for the case without AC and 14% to -1% for the case with two ACs in the source room. The former figures mean that, without AC, when the multi-zone temperature difference was smaller than 0.1°C, the UFP exposure in the clean room was less than 62% of the exposure in the source room. But when the multi-zone temperature difference was increased to 1°C and 2 °C, the UFP exposure in the clean room was close to 90% of that in the source room. The negative value of S means that the UFP exposure in the source room was lower than that in the clean room, which occurred when two ACs were running in the source room.

In conclusion, indirect connection between the source room and the clean room partly isolates tobacco smoke UFP from the clean room. Furthermore, a smaller multi-zone temperature difference results in more UFPs being isolated. Additionally, although the apartment structure can to some degree isolate pollutants, the CADR should be chosen according to the whole apartment's volume to avoid low S values induced by large multi-zone temperature differences.

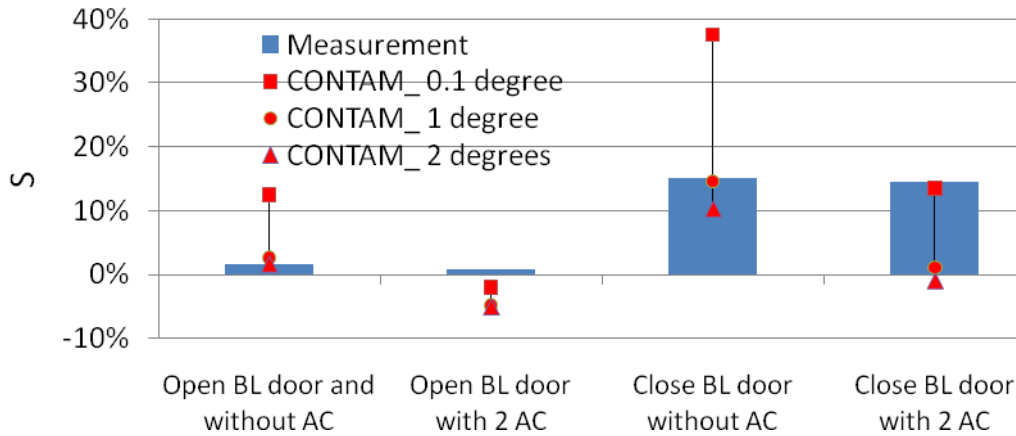


Figure 5. UFP exposure difference (S) between source room (living room) and clean room (bedroom). The ACs were located in the source room.

1.3 Indoor air isolated

In one case the pollutants were close to completely isolated, i.e. when smoking in the kitchen and keeping the K door closed. The results show that less than 3% of the UFPs infiltrated from the polluted kitchen to the bedroom (see Figure 6) regardless of whether an AC was in operation in the kitchen, or not. Thus, in this case the previously described S-value was higher than 97%. Therefore, an easy solution to SHS exposure appears to be smoking in kitchen while keeping the K door closed. With the K door open there was practically no difference between the exposure in the kitchen and in the bedroom, i.e. the S value is about 0%. This was most probably due to large temperature differences between the rooms.

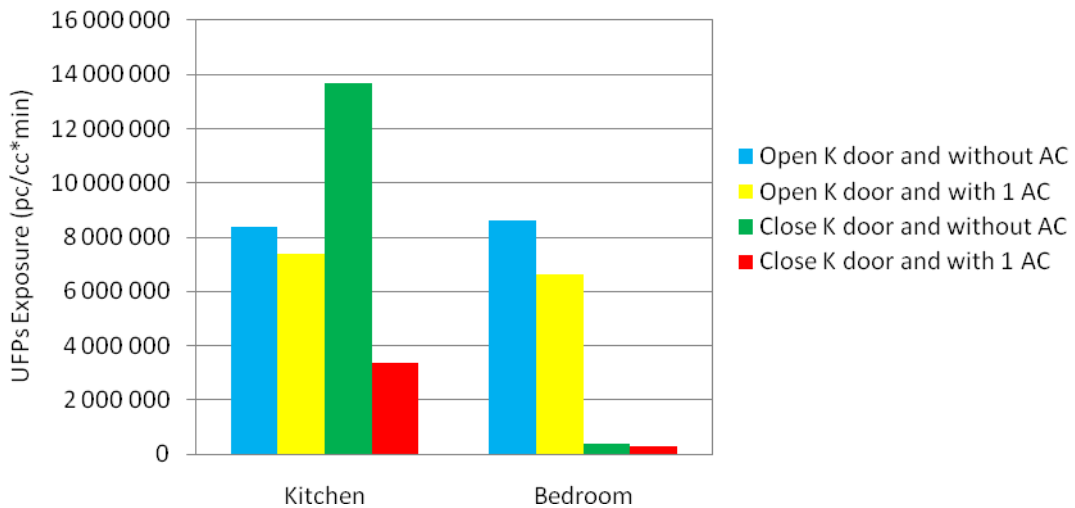


Figure 6. UFP exposure in kitchen and bedroom with open and closed kitchen (K) door. The AC was located in the kitchen. The source was located in the kitchen.

2. Air cleaner effectiveness H

The exposure in the kitchen was reduced by 76% by using one AC when keeping the K door closed; see the data in Figure 6. Similarly, the exposure in the living room was reduced by 64% by using one AC when keeping the BL door open; see the data in Figure 7. The kitchen

was smaller than the living room and also isolated by the K door being closed, which explains the larger exposure reduction in the kitchen. Using one AC, the UFP personal exposure was reduced from $6.9 \cdot 10^6$ pc/cc·min to $2.5 \cdot 10^6$ pc/cc·min during a 3h period, when the BL door was open. Additional experiments showed that when two ACs were used, the exposure dropped to $2.1 \cdot 10^6$ pc/cc·min. The AC reduced the indoor UFP exposure close to the outdoor exposure level, see Figure 7. In the experiments, ambient UFP concentration was about 10^4 pc/cc.

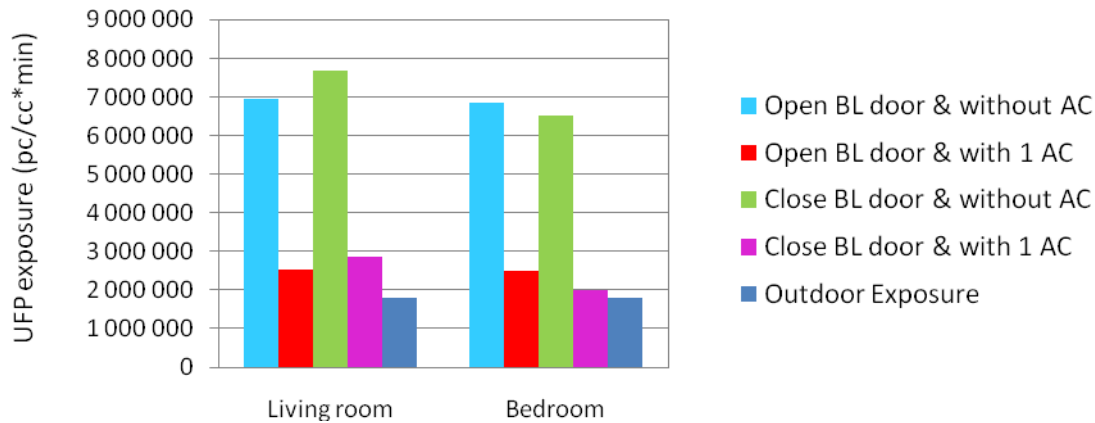


Figure 7. Indoor UFP exposure during 3 hours for the above cases. Source room = living room, clean room = bedroom. The AC was located in the living room.

For to these well-mixed cases, the AC effectiveness H in the whole apartment was calculated by Equation 2, which is defined by Miller-Leiden et al. [6]. Here, C_{ac} is the indoor concentration with AC; $C_{no\ ac}$ is the indoor concentration without AC. The effectiveness H for one AC and two ACs are shown in Figure 8.

$$H = 1 - \frac{C_{ac}}{C_{noac}} \quad (2)$$

The AC effectiveness under stable conditions was 80% for one AC, and 93% for two ACs; see Figure 8. Note that it took more than 1.5 h before steady-state conditions were reached. During this period the AC effectiveness, H , was substantially lower than the maximum value.

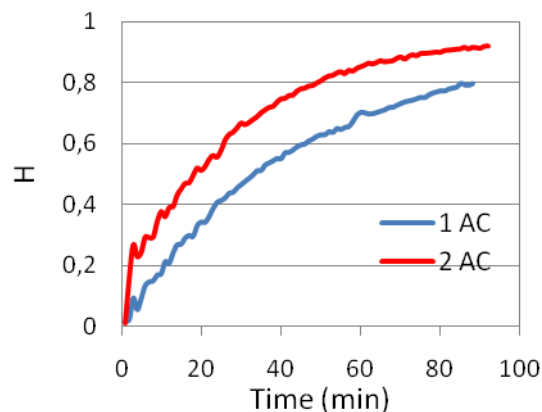


Figure 8. The air cleaner effectiveness H for one AC and two ACs

3. Influence of AC location relative to the pollution source

The relative location of AC to pollution source is another factor influencing UFP exposure. The UFP exposure reduction percentage (R) is defined by Equation 3, which evaluates UFP exposure reduction in one room by comparing UFP exposure with AC ($E_{with\ AC}$) and UFP exposure without AC ($E_{without\ AC}$).

$$R = 1 - \frac{E_{with\ AC}}{E_{without\ AC}} \quad (3)$$

Figure 9 shows values of R, calculated for the clean room (bedroom) and the source room (living room). Data are shown both for the case with two ACs located in the living room and for the case with two air cleaners located in the bedroom. The BL door was closed in all of the cases. Similar to the analysis of the parameter S, the influence of room temperature differences was also analyzed by CONTAM simulations. When tobacco smoking occurred in the living room, and two ACs were located in the bedroom, a relatively isolated clean environment was developed in the bedroom (R about 85% in the bedroom and 45% in the living room). This situation can be expected to result in a rather low cleaning effectiveness in the whole apartment regarding UFPs. While operating the AC in the source room (living room), the exposure-value in both the living room and in the bedroom was about 70%. It can be assumed that also all other rooms would show similar R-values, i.e. a rather large exposure reduction in the whole apartment.

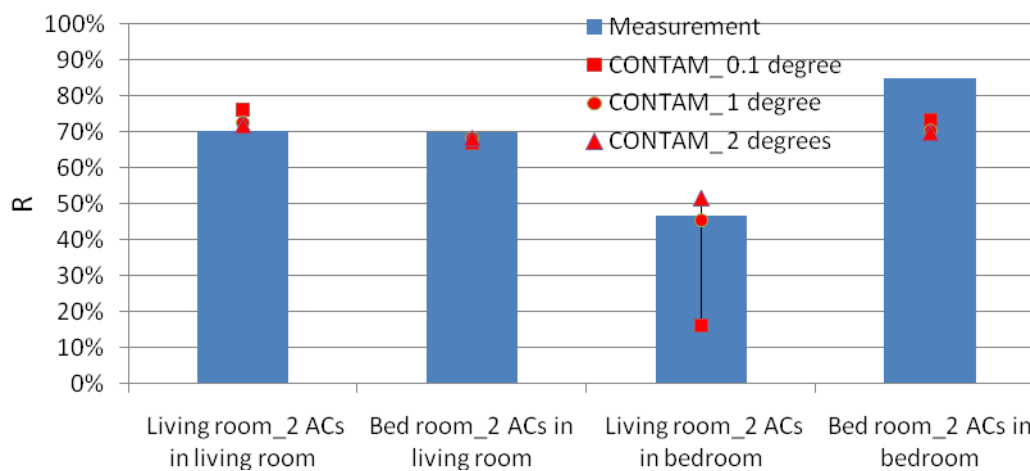


Figure 9. UFP-exposure reduction percentage (R) for different locations of the ACs

CONCLUSION

For this apartment ($V=110m^3$), one AC ($CADR=240m^3/h$) was, in most of the studied cases, enough to reduce the indoor UFP exposure by about 65%-75% in individual rooms. The highest exposure reduction, $R=85\%$, was observed when two ACs were used in the bedroom when keeping the door between the bedroom and the living room closed.

The lowest exposure reduction, $R=12\%$, was observed when using one AC in the kitchen and keeping the kitchen door open while smoking took place in the kitchen. Isolation of the

kitchen by keeping the door closed increased the exposure reduction obtained by the AC to 76%. In this case, when the kitchen door was closed, the exposure to smoke particles in non-smoking rooms was only a few percent of the exposure in the kitchen. When the kitchen door instead was left open, a massive spread of particles within the apartment was observed. The particle spread is due to large inter-zonal air flows induced by large temperature differences between rooms.

Although the apartment structure could, to some degree, isolate pollutants, the CADR should preferably be chosen according to the whole apartment's volume. Furthermore, the ACs should be placed in the same room as the strongest particle source. For example, operation of two ACs in the living room, where cigarettes were smoked, reduced the UFP exposure by about 70%, both in the source room and in the adjacent non-smoking bedroom. The total capacity of the two ACs corresponds to 4.4 air changes per hour, expressed as an average value for the entire apartment. This is about ten times the ventilation air change rate.

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