Investigation of indoor aerosols emitted from electrical appliances

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Abstract. Air quality inside a residential apartment has been investigated by measuring the PM emission generated from cooking and ironing using electrical devices. The samples were collected in the kitchen, the living room and the bedroom. The total number concentration, the size distributions and mass concentration PM0.1, PM2.5 and PM10 were measured using portable and compact instruments; a NanoScan SMPS 3910, an Optical Particle Sizer 3330 and a Condensation Particle Counter 3007. The results were analyzed and compared to the WHO guidelines for ambient air quality. In the absence of a standardized method for assessing indoor air quality, a procedure is suggested for a better consideration of the physical properties of the particles. The results obtained showed that an electrical oven with visible heating electrical resistances inside is much more emissive compared to a cooktop plate or a steam-iron were the heating resistances are protected in a steel housing. The emission from the kitchen spreads all over the apartment and the concentration levels remain high for a long time. The dissemination of particles is accompanied by a growth in their size. Ventilating the areas, for example by using a hood or opening a window, seems an efficient measure to reduce the high concentration of particles emitted by residential activities.

1. INTRODUCTION

Restriction policies for the mass safety in a disease outbreak have limited people’s activities outside forcing them to stay at home longer. While this led to a clear decrease of outdoor air pollution, by staying at home for longer time, people are exposed for extended periods to indoor fine and ultrafine (UFP) particulate matter (PM) emitted by indoor sources associated with anthropic activities. For a long time, the focus was mainly on outdoor air pollution. However, there is an increasing interest in the measurement of air quality also indoors since people are spending long times inside buildings even longer than outside. The purpose of this study is to show the capabilities of commercially available technical solutions for counting and sizing aerosols emitted by common indoor particle sources related to cooking and ironing. Cooking activities are one of the major sources of indoor particle emissions, while PM emission from ironing is not much investigated [1]. Nowadays it is clear that PM inhalation is a health risk related not only due to their chemical composition but also to their small size which allows for penetration into the deep length and subsequent deposition. Epidemiological analysis studies indicate that exposure to PM from anthropogenic sources leads to an average loss of 8.6 months of life expectancy in Europe ([2], [3], [4]). Submicron PM categories and also UFP of less than 100 nm in particle diameter have been attracting researchers’ attention ([5], [6]). In fact, UFP can stimulate the immune system by crossing the epithelial barrier [7] and the lining of the blood vessels to be distributed to different vital organs and even brain cells ([8], [9]). This study is focusing on the PM emission from...
an electrical cooktop (2×1 kW and 2×1.5 kW), a mini electrical oven (2kW) and an electrical steam iron machine (1.63 kW). The measurements of PM emissions are performed using the portable Scanning Mobility Particle Sizer (SMPS) spectrometer NanoScan SMPS (Model 3910) for sizing nanoparticles an Optical Particle sizer (OPS, Model 3330) and a handheld Condensation Particle Counter (CPC, Model 3007), all manufactured by TSI Incorporated (Shoreview, MN, USA). The combination of these instruments allows an easy investigation of a broad range of particles in the size range from 10 nm to 10 µm, so including UFP. Different levels of PM10, PM2.5 and PM0.1 are reported. Also, the total number concentrations in particle/cm³ and size distribution obtained by the merging the data from NanoScan and OPS are investigated. It should be pointed out that a standardized method for indoor PM emission measurement is still lacking due to the complex release and dispersion of PM from indoor sources and the variations of local site conditions.

2. MATERIALS AND METHODS

Submicron particle sizes were measured based on the electrical mobility of the particles using the NanoScan SMPS [10], which covers a size range from 10 nm to 420 nm with 13 size channels per size distribution and a detection limit up to 10⁶ particles/cm³. The measured size range is extended to coarse particles using the OPS, which covers a size range from 300 nm to 10 µm with 16 size channels per size distribution with a detection limit up to 3000 particles/cm³. The OPS measure an optical equivalent diameter, which is often different from the electrical mobility diameter measured by the SMPS technique. To facilitate reviewing, averaging, merging and post-processing of the data, the Multi-Instrument Manager (MIM™) software introduced by TSI Incorporated is used [11]. One of the key features when merging OPS data with NanoScan data is that the MIM software can be used to determine an overall aerosol effective refractive index (RI) and shape factor (SF) to fit the merged data. The optical properties of the aerosol identified can then be implemented into the OPS to match the measured sizes as close as possible to the known aerosol sizes and correct the mass concentrations PM10 and PM2.5 accordingly. The CPC used in this study is the reference instrument for counting particles. It has a D₅₀=10 nm, which corresponds to the minimum detectable size of the NanoScan. Its maximum concentration measured exclusively in a single count mode is 10⁶ particle/cm³. The total PM concentration is measured on a 1 second time base which allows gaining insights on the short-term events and the dynamic of the particles. A dilution of 4:1 was implemented since the PM concentration could exceed the upper limit of the CPC. For the purpose of comparison, 1Hz data from CPC/NanoScan were averaged on a one-minute time base. All instruments used in this study had a valid factory calibration, were tested to be leak free and operated with the correct inlet flow rates. The wicks for the CPC and the NanoScan were replaced regularly to avoid humidity contamination.

The measurements were performed inside an apartment of 87 m² situated in the city of Orléans in France during spring time. The outside temperature was ranging from 10°C to 25°C with an ambient humidity below 40%. The temperature inside the apartment was controlled to a stable 19°C. The measurements were performed in the kitchen, in the living room and in the bedroom (Figure 1) following the scenario below:

![Figure 1. Drawing of the apartment and location of the measurement areas.](image-url)
• Emission measurement in the kitchen:
  - From the oven heating up to 185°C-200°C using both top and bottom electrical resistances, with a fan generating a mechanical convection heating. The electrical resistances are visible and not protected.
  - From the electrical cooktop plate where the electrical resistances are protected within a steel cover
  - From the oven and the cooktop plate running simultaneously

• Measurement in the living room while cooking in the kitchen and while ironing

• Measurement in the bedroom while cooking in the kitchen using the oven and the cooktop plate.

3. RESULTS

The total number of particle concentrations were first compared between the reference CPC and the NanoScan based on the Pearson correlations coefficient [12]; a coefficient greater than 0.9 means a good similarity between the measurement. Size distributions from the NanoScan and OPS were also analyzed to depict the impact of the main scenario events on the size of particles. After applying the optical correction to the OPS data, the mass distributions were then calculated from the combined NanoScan and the OPS size distribution assuming a density of 1.4 g/cm³ [13] and spherical particles. The particle mass concentration variations on time for PM0.1 (for UFP ≤100 nm), PM2.5 (for particles ≤2.5 µm) and PM10 (for particles ≤10µm) were then calculated. In general, the PM0.1 information is extracted from the NanoScan. However, the OPS (and NanoScan) data are used together for calculating the PM2.5 and PM10 mass concentrations. The mass information was compared to the recommended limit values reported by WHO guidelines [2]:
- PM2.5 should be less than 10 µg/m³ (annual mean) or 25 µg/m³ on a 24-hours mean.
- PM10 should less than 20 µg/m³ annual mean and 50 µg/m³ on a 24-hours mean base.

3.1. Emission measurement in the Kitchen

The kitchen has a total floor space of 18 m² and a volume of 30 m³ (6 m×2 m×2.5 m). The instruments were located in the center of the kitchen; at 0.85 m from the ground, 2m away from the electric cooktop plate and 3 m away from the mini electrical oven.

3.1.1. Emission from the mini electrical oven. The mini electric oven was running to heat up water placed inside on a metallic container to simulate a cooking process. Additional tests without water inside the oven were also considered. The measurement instruments were synchronized to the computer clock and the acquisition was started at the same time for a total duration of one hour. Data acquisition was started before turning ON the oven to get the background ambient concentration as a baseline and characterize the increase of concentration once the oven is started. The acquisition was also continued after stopping the oven to see how long it takes to the concentration to go back to the background levels. The results of the total concentrations measurement, repeated three times, are reported in Figure 2:
- The 3 m distance separating the instrument from the oven has led to a delay of couple of minutes in detecting the increase of particle concentration by the instruments.
- The concentration reached values as high as 3×10² particle/cm³ with water inside the oven (Figures 2a, 2b) and 6×10² particle/cm³ without (Figure 2c). The water vapor seems affecting the PM emission from the oven.
- The emission process was quite dynamic: the CPC detected several spikes up to ~5×10⁵ particle/cm³ that the NanoScan couldn’t detect due to its longer measurement interval.
- A big difference was noticed between the results from the CPC and the NanoScan (Figure 2) with a Pearson correlation coefficient of 0.76 for the cases with and without water inside the oven. Since the difference appears only when the oven is running, with no significant increase in concentration from the OPS (Figure 2a), this could be explained by the high electrical charges of the particles emitted from the electrical resistances which seems affecting the charging performance of the corona charger in the NanoScan in a way that the equilibrium charge state could not be achieved easily. This is impacting directly the concentration reported by the NanoScan. To overcome this, an additional soft X-Ray neutralizer (Model 3088, TSI Inc.) was used as a pre-neutralization step prior
to sampling by the NanoScan (Figure 3a). This improved the total concentration measurement (Figure 3b) showing a better agreement between the CPC/NanoScan with a Pearson coefficient of 0.98. The size distributions from the OPS/NanoScan (Figure 3c), showed an abrupt shift of the size mode toward smaller sizes when the oven is switched on, basically from ~100 nm to ~50 nm. The OPS did not show an important increase of concentration which confirms that the emission from the oven were mainly in the submicron range, and particularly below 200 nm. The oven was running for 25 min. After turning it off, it took ~30 min for the concentration to go back to the background level of around 3000 particle/cm³.

Particle mass information is reported in Figure 4 after applying the optical corrections to the OPS data based on MIM outputs (SF=0.8 and RI=1.98). The correction led to a down shift of PM10 concentrations as shown in the curve “Difference” PM10 (%) in Figure 4.
When the oven was running, the mass concentration values exceeded the day limit values for PM10 and PM2.5 reaching respectively ~97 µg/m³ and ~94 µg/m³. PM0.1 shows also a maximum of 91 µg/m³ which emphasize that UFP are the most dominant particles in the emission process here since PM2.5 and PM10 integrates already the PM0.1 fraction.

3.1.2. Emission from the electrical cooktop plate: The tests were performed without using the additional neutralizer. One heater of the cooktop plate was turned on (1.5 kW) without anything being cooked/heated up on top of it. The instruments were placed in ~2 m distance from the cooktop plate and were sampling during 1-hour. The first 8 min corresponds to the background measurement, then the cooktop plate was turned on for 17 min and the sampling continued afterwards. Before stopping the acquisition, the window in the kitchen was opened. The total number concentration curve in Figure 5a shows the following:

- The concentration started to increase ~4 min after the cooktop plate was turned on.
- The CPC and NanoScan concentration matched nicely with a Pearson coefficient of 0.95. The PM emission comes mostly from the heated housing plate of the electrical resistance.
- The particle number concentration reached a maximum of ~1.5×10⁵ particle/cm³ on the 1-min averaged data with instantaneous spikes going up to 2.5×10⁵ particle/cm³ from the real time CPC data. These values were much lower than what the oven generated without water inside (Figure 2c).
- The window opening clearly accelerated the decay of the particle concentration to more than half in about a minute (Figure 5a).

Figure 4. PM10, PM2.5 and PM0.1 emission from the oven.

Figure 5. Particle emission from the electrical cooktop plate heater (1.5 kW);
(a) Total number concentration NanoScan/OPS /CPC; b) Merged OPS/NanoScan size distributions.
Size distributions reported in Figure 5b show that the cooktop plate generated a wide range of particle sizes from <10 nm up to ~400 nm with a mode at ~40 nm. Mass measurement reported in Figure 6 and calculated after correction of OPS data (RI=1.96; SF=0.87) shows a lower emission compared to the oven previously, below the limit values for PM10 and PM2.5, with a lesser contribution from PM0.1.

3.1.3. Combined emission from the oven and the cooktop plate: The cooktop plate was first started, then the oven and both were stopped at the same time. In this test, both systems were heating up without having any food being cooked to avoid additional interaction with additional particles emitted by the cooked ingredients. The total concentration reported by the CPC (Figure 7a) showed a dynamic emission with values reaching a maximum of \(8.5 \times 10^5\) particle/cm\(^3\) which is much higher than the results obtained previously (Figures 2c and 5a). A good match between the CPC and the NanoScan is obtained when only the cooktop plate was used. However, after starting the oven both curves showed a difference of ~50% with the NanoScan counting less particles. This confirms the previous observation from the test with the oven where the difference lead to a calculated Pearson correlation factor of 0.85.

Looking at the size distributions (Figure 7b), the emission from the oven showed a shift of the size mode below the lower limit of the NanoScan when the oven was started. Some size distributions showed multiple modes below 100 nm which could be related to different origins of the emitted particles.
Mass concentration (Figure 9) was found systematically higher than the limit values for PM2.5 when the electrical devices were running. However, the overall PM10 values were close to the limit value.

3.2. Measurement in the living room

3.2.1. Measurement in the living room while cooking pancakes in the kitchen: The instruments were placed in the living room, which is connected to the kitchen by the doorway D1, which was kept open for the tests (see “Test Area 2” in Figure 1). One heater (1 kW) from the cooktop plate was used. The data were acquired continuously for a total duration of two hours. Figure 10 shows a good match between the different number concentrations even for large particles measured by the OPS (Pearson coefficient of 0.99). It took a longer time, around 10 min, for the instruments to start seeing particles from the cooking process. In this test, the cooking process seems generating higher concentration of large particles compared to the measurement performed in the kitchen. This may also infer an agglomeration effect of small particles while travelling from the kitchen to the living room.

After stopping the heater on the cooktop plate, it took nearly 5 min for the concentration to start decreasing, and nearly an hour to go back to the background levels. The mass concentrations shown in Figure 11, exceeded again the day limits by far, reaching a maximum value of nearly 180 µg/m³. Opening the window in the kitchen accelerated the decay of the concentration.

The size distributions measured by the OPS/NanoScan are represented separately this time in Figure 12 to better visualize, using the appropriate scale for concentration values, the presence of large supermicron particles during the cooking process.
The size distribution from the NanoScan (Figure 12b) showed a dominance of UFP with a mode shifting to ~50 nm during the cooking process. The concentration values from the OPS (Figure 12a) were found two orders of magnitude less than the NanoScan concentration values but still higher than the tests done in the kitchen.

3.2.2. Measurement in the living room while ironing: Ironing is one of the most simple and common household activities taking place indoors. During an ironing activity, the user is directly exposed to the emission from the iron, even for a shorter time compared to a cooking process. The steam iron system used is a commercial model with a total power of 1.63 kW, equipped with a steam production function. The measurement systems are placed at 50 cm from the iron at the same level of height. Windows were kept closed. The total concentration of particles emitted during the ironing activity (Figure 13a) showed a rapid increase of concentration after starting the iron: the background values jumped by more than one order of magnitude from ~3.10³ particle/cm³ to 4.10⁴ particle/cm³. When a steam jet was generated by the iron, a spike of concentration was detected by the CPC with maximum values going up to 3.10⁵ particle/cm³. A few minutes later, the OPS also showed a much slower increase of the concentration.

The steam function was used four times corresponding to the peaks of high concentration detected by the CPC (Figure 13a). The values remained quite high after 10 min from switching off the electrical iron.

![Figure 13. a) Total concentration of particles emitted during the ironing activity; b) Merged size distributions variation on time; c) Mass concentration variation over time.](image)

The optical correction of the OPS data (SF=0.8 & RI=1.98) had a direct and non-negligible impact on the PM10 values bringing back the mass concentration below the limit values (Figure 13c). Overall mass concentration was acceptable for PM10 and PM2.5 except when steam vapor is generated, with spikes reaching concentration levels as high as 150 µg/m³ being detected.

3.2.3. Measurement in the bedroom while cooking in the kitchen: The purpose of the test here was to investigate how the emitted particles from a real cooking process in the kitchen travel along the apartment to reach the farthest point from the kitchen which is the bedroom (“Test Area 3” - Figure 1). During this test, the door D2 was kept closed and D1 was open. The instruments were placed in the bedroom and sampled continuously for a total duration of ~4 hours. A quite dynamic cooking scenario
was considered involving the oven and the cooktop plate with two different heaters (i.e. “Cooktop 1 – 1 kW” and “Cooktop 2 – 1.5 kW”). The main events of the cooking scenario are shown in Figure 14.

A lower number concentration of particles was measured in the bedroom compared to the previous tests with less variation in amplitudes (Figure 14). The oven seemed the main driver for the increase of particle concentration compared to the cooktop plate as each start of the oven was followed by an increase in concentration. It took ~20 min for the instruments to start detecting the increase of particle concentration in the bedroom and almost 30 min for the second particle concentration increase. The OPS could detect the presence of large particles at much higher concentration than what was detected in the previous tests in the kitchen. Those could come from the cooking process itself or could be linked to a possible coagulation of smaller particles coming from the kitchen into bigger ones that could travel along the apartment to reach the bedroom. The bigger particles are aerodynamically slower than the smaller ones which explains the longer delays for detecting them by the OPS. At the end of the cooking process, the window in the bedroom was opened during the acquisition and this led to a decrease of concentration and shift toward bigger sizes in the size distributions (Figure 15). Here also the emission from the oven shows a shift toward lower sizes with a mode at ~50 nm.

Mass concentrations are reported in Figure 16 at two main time intervals corresponding to the start of the cooking process (Figure 16a) and at the end of it (Figure 16b).
Even though the test showed how far the emitted particles can be transported within the apartment, the overall concentration values measured in the bedroom were found mostly below the recommended day limit PM2.5 and PM10 values. Also, the efficiency of ventilation was again proven here for the removal of the remaining suspended particles.

4. Conclusion
This study presented an assessment of indoor particle emissions caused by common anthropogenic activity. The results obtained confirmed that the design of the electrical home appliance could have a direct impact on the magnitude of the particle contamination in indoor air; heating devices with non-protected electrical resistances seem to be a strong cause of high indoor particulate levels. For this type of system where aerosols are potentially highly charged, a special care to the charging state of the aerosol must be considered. The RI and SF corrections applied to the optical size distributions offered a realistic description of the aerosol emission with, interestingly, lower levels of emission for some cases below the limit values for PM10. The measurement quality assurance using a reference standalone CPC is found helpful and needed for this type of application. While these emissions are dominated by UFP, the total concentrations exceeded the recommended limit values for PM10 and PM2.5 by far. Natural and/or mechanical ventilation, especially by the use of kitchen hoods, have the potential to contribute to making the indoor environment cleaner.

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