SIZE DISTRIBUTION OF COOKING GENERATED ULTRAFINE PARTICULATE MATTER AND THEIR DISPERSION THROUGHOUT THE SPHERE HOUSE

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ABSTRACT

Cooking is a major source of indoor aerosols and thus has strong implications on public health. A series of cooking experiments were performed within a well instrumented house (SPHERE) and measured the size distributions of the particulate matter and particle number concentrations during the cooking and post-cooking periods. Cooking activities generated rapid increases in ultrafine particle number concentrations (10^5–106 cm^{-3}), followed by measurable inter-room and inter-floor transport with observable time delays and attenuation between source and receptor locations. The measurements of the size distributions of the ultrafine particulate matter by Scanning Mobility Particle Sizer and Counter (SMPS+C) from cooking experiments showed that frying cooked meal produced more aerosols with smaller size, at least one order of magnitude larger in number and two-fold smaller in size than the oven cooked meal. Frying generates rapid increases in particle number concentration and is transported to other areas of the building, often several orders of magnitude above background levels. Although transient, cooking represents a major contributor to short-term exposure, particularly for ultrafine particles. Ventilation significantly reduced particle concentrations, particularly in the source room, although variability increased in locations further from the source.

Keywords: kitchen, ultrafine particle, indoor pollution, frying, size distribution, decay, exposure.

1 INTRODUCTION

Particulate matter (PM) is a key pollutant in the indoor environment due to exposure and impact on human health. Food cooking has been widely recognised as one of the dominant indoor sources of PM emissions [1]–[6]. High-temperature cooking activities such as frying and grilling can generate large quantities of ultrafine (particles below 100 nm in diameter) and fine particles (particles ≤2.5 μm in diameter), often producing rapid and substantial increases in particle number concentration and short-term exposure peaks [2], [7]–[11]. Tang et al. [12] reported ultrafine particle number concentrations on the order of 10^5–10^6 cm^{-3} during cooking activities, while corresponding $PM_{2.5}$ concentrations ranged between 26.7 and 92.9 μg m^{-3} depending on the cooking method. The cooking emissions arise primarily from the thermal decomposition of cooking oils and food components, leading to the formation of both organic aerosol particles and combustion by-products. The cooking emissions are dependent on fuel type (e.g. gas, electric), ventilation condition and cooking duration and they are highly variable in particle size distribution, concentration, and chemical composition, and that exposure magnitude depends strongly on contextual factors within the dwelling [13]. Although the sources and health relevance of indoor PM is well studied, there remains limited experimental understanding of how particles generated indoors disperse within realistic building environments under varying source and ventilation conditions, particularly for submicron and ultrafine particle fractions.

Since, majority of people spend their time mostly (80–90%) in indoor [14], [15] and the dispersion of the pollutants in the house can be directly affected by several factors (e.g. design of the buildings, insulation, ventilation), it is important to characterize the dispersion of the

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PM originated from food cooking throughout the house before decaying. In residential settings, cooking often dominates short-term particle exposure, producing sharp concentration peaks that can exceed background levels by several orders of magnitude [8], [11]. The kitchen particle concentrations may exceed those in adjacent rooms by 40–70%, with concentration gradients influenced by particle size and airflow pathways [16]. Aerosols generated in ground-floor kitchens may be transported upward through staircases via buoyancy-driven convection or pressure-driven airflow, potentially reaching upper-floor bedrooms and affecting exposure during resting or sleeping periods [17]. Recently, Vesisenaho et al. [18] showed the decay period following cooking emissions accounting for approximately 67–83% of the daily cooking-related lung-deposited surface area dose, which highlights the importance of considering not only peak emission events but also the subsequent dispersion and removal processes that determine particle persistence within indoor environments.

Exposure to cooking generated PM can be responsible for respiratory health effects [19], [20], thus the information of the dispersion of the PM and the size distribution of the PM emitted from cooking activities is important to know how this can affect level of individual exposure. In the study, we describe a series of food cooking experiments within a well instrumented house that use aerosol measurements and investigate the size distribution of PM (0.01–10 μm) generated from food cooking and their decay and the changes of each particle size over time. The size-segregated PM number and their variation throughout different food cooking activities and dispersion between rooms of the house are also discussed.

2 EXPERIMENTAL

The food cooking experiments were conducted in the kitchen of the SPHERE house on 20, 21 July 2016 and 27 February 2025. Cooking was performed using standard domestic appliances under realistic indoor conditions. The appliances were thoroughly cleaned before starting cooking experiments which effectively eliminate residual PM from prior use. More details about SPHERE house (https://www.bristol.ac.uk/research/groups/digital-health/research/sphere/) and the deployment of the instruments can be found in Matthews et al. [21].

For the experiments during 20 and 21 July 2016, a Grimm Scanning Mobility Particle Sizer (SMPS+C) was placed in the kitchen, on a work bench in the corner near the sink and window. On 20 July 2016, a meal of pasta, fried beef and fried onions using cooking oil was cooked. On 21 July 2016, a meal of oven baked chicken and potato was cooked. The details of the cooking activities for the time period of 20–21 July, 2016 can be found in Matthews et al. [21]. SMPS+C measurements allow a size distribution of aerosols created to be measured, and the decay and changes of size of each particle are studied. Particle concentrations were measured at 1 s intervals in the kitchen and contemporaneously in the hall of guest bedroom with a TSI 3007 condensation particle counter (CPC; USA).

For the experiment during 27 February 2025, the SMPS+C was positioned in both the kitchen (source room) and master bedroom (receiving room) at approximately 1 m above floor level, representing the breathing zone. It was positioned in the kitchen approximately 0.5–1 m from the cooker, representing near-source conditions at breathing height. An Electrical Low Pressure Impactor (ELPI, Dekati, Finland) was placed at floor level in the kitchen to characterise real-time aerodynamic size distributions of emitted particles. The DustTrak DRX (TSI, USA) was also located in the kitchen, positioned approximately 0.5 m lower than the ELPI sampling point, measuring particle mass concentration (PM_1, $PM_{2.5}$, PM_{10}). TSI CPC instruments were deployed in the master bedroom and outside the bathroom to capture high time-resolution variations in particle number concentration associated with inter-room transport.

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Figure 1: Layout of the two-storey SPHERE House showing instrument deployment for the experiments performed on 27 February 2025. The instrumental deployment for the experiments performed on 20 and 21 July 2016 can be found in Matthews et al. [21].

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Table 1: The cooking activities, ventilation conditions, and experimental structure for 27 February 2025 experiment.

Exp. no	Exp. type	Cooking activity	Fan	Key cooking stages	Typical duration	No of repeats
1–6	Onion ring deep frying	Deep frying onion ring	Fan off/ Fan on	Oil heating; deep frying; cooling; controlled ventilation	~22 min per repeat	3 per condition
7, 8	Stir frying	Stir frying chicken, vegetables and noodles	Fan off/ Fan on	Stove heating; sequential ingredient addition; active stir frying; post-cooking ventilation	~30 min per experiment	1 per condition

3 RESULTS AND DISCUSSION

3.1 Aerosol number and size distribution decay

The production and decay of particles during two cooking events (20 July and 21 July 2016) (Fig. 2) show a sharp increase during cooking events and then decay. The increment of particle number concentration coincides with the decrease of particle size e.g. a drop of mean particle diameter from 35 to 17 nm and 40 to 30 nm during the cooking on 20 July and 21 July, respectively suggesting that the food cooking produces a significant amount of ultrafine PM as suggested by Long et al. [22], Olson and Burke [23] and Patel et al. [24]. The $PM_{2.5}$ and submicron PM generated from cooking in the study (10 to 807 nm, Fig. 2) is comparable with the study of He et al. [25] who found 7 to 808 nm PM from cooking activities in 15 houses in Australia. The frying can produce even smaller PM (two-fold lower) than oven cooking. Thus, the PMs emitted from food cooking in the study can penetrate into the lung, irritate and corrode the alveolar wall and consequently impair lung function of the people living in the house [26], [27].

The particle size increases and the particle number concentration decreases over time (Fig. 2) as smaller particles produced by cooking in the kitchen are lost due to deposition (diffusion) on the surface and/or coagulated to the larger particulate matters [28]. The cooking on both 20 and 21 July both produce submicron particulate matter in the size range between 0.01 and 1μm, but the patterns of their peaks are different. On 20 July, a sharp increase of PM at 23:37 LT is seen at the time of frying onions and a peak at 23:44 LT is found before starting of frying meats. Thus, the contribution of frying onions to the submicron PM is significant which is consistent with the study of Allan et al. [29] who found the larger contribution of cooking oils to PM than the meat itself in urban areas of London and Manchester. On 21 July, a broad peak is found with a maximum at 23:59 LT after 30 minutes cooking time suggesting that the oven cooked meals can produce PM slowly compared with frying meals. The particle number concentrations of the submicron PM produced on 21 July is found to be at least one order lower than that produced on 20 July, which is not surprising as there is no usage of cooking oil for preparing oven cooked meal.

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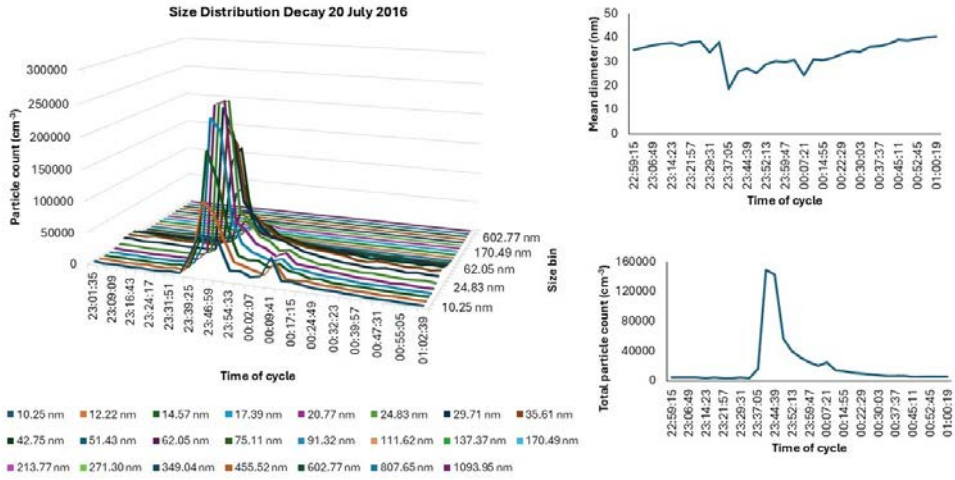
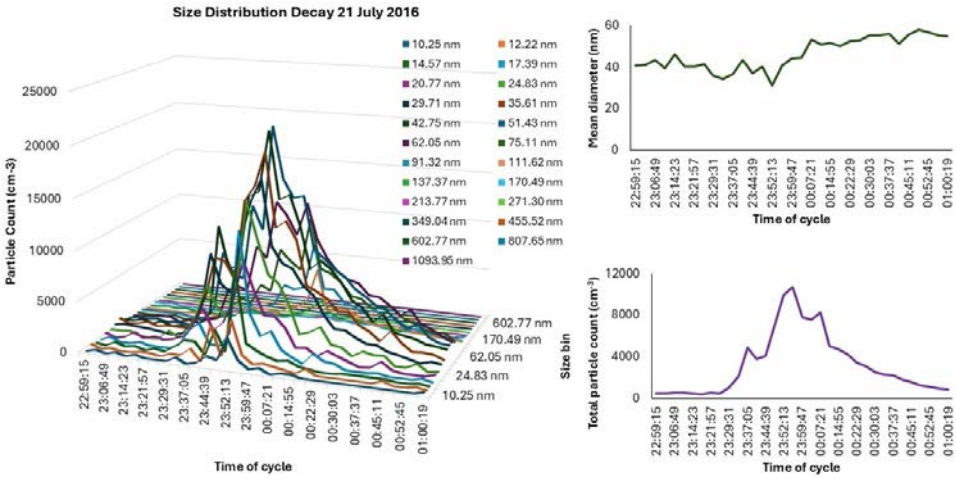


(a)



(b)

Figure 2: Size distribution decay over time measured with the SMPS+C system during cooking on 20 and 21 July. (a) Shows the variation of mean particle diameter over time; and (b) shows variation of the total particle count over time.

3.2 Aerosol generation from frying and distribution (deep frying vs stir frying)

During deep frying on 27 February 2025, particle concentrations in the kitchen increased sharply. In several experiments, concentrations exceeded 1×10^5 particles cm^{-3}, particularly immediately after the onion ring was introduced into the hot oil. ELPI measurements showed higher peak concentrations than the SMPS+C, reflecting its sensitivity to a wider particle size range and its faster response to rapid changes in concentration. Shortly after the kitchen peak, increases in particle concentration were observed in both the master bedroom and bathroom. CPC measurements showed that particles reached the upper floor within minutes, with peak

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concentrations in the bedroom reaching approximately 5×10^4 particles cm^{-3}, corresponding to 30–50% of the kitchen peak. PM_1 concentrations measured using the DustTrak DRX reached approximately 500 ± 100 µg m^{-3}, confirming that deep frying generates not only high particle number concentrations but also significant particulate mass. The higher mass concentrations observed during deep frying reflect the contribution of semi-volatile organic material and liquid aerosol droplets formed at elevated oil temperatures [30].

The temporal evolution of particle number concentration during deep frying (Fig. 3) showed that each frying cycle produced a sharp increase in particle concentration, followed by a gradual decrease after cooking. Deep frying involves heating a larger volume of oil to higher temperatures, which could increase the release of VOCs and promotes particle formation through nucleation and condensation processes. As a result, large numbers of UFP are generated over short time periods, leading to rapid increases in indoor particle concentration. Clear differences were observed between experiments conducted with and without the extraction fan. In experiments without the fan, particle concentrations remained elevated for longer periods and decayed more slowly. In contrast, the use of mechanical ventilation resulted in a faster reduction in particle concentration following cooking. This pattern was consistent across all repeat experiments. Small differences in peak timing between instruments arise (Fig. 3) due to differences in measurement principles and sampling intervals. The SMPS-C reports size-resolved concentrations over a scan period, whereas the CPC and ELPI respond more rapidly to changes in concentration. Despite these differences, all instruments show consistent overall trends.

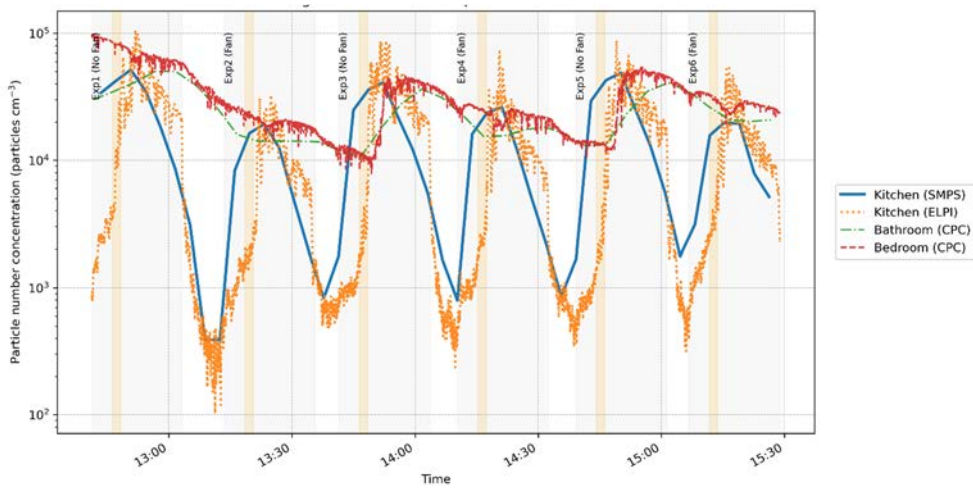

Figure 3: Time-resolved particle number concentration measured during onion ring deep frying experiments (Exps 1–6) using SMPS+C, CPC and ELPI. Light grey shading indicates the duration of each experiment, while orange shading highlights the active frying period. Vertical dashed lines indicate the onset of ventilation.

Peak particle concentrations before and after ventilation were compared using a paired statistical test to assess the significance of ventilation-driven removal. Paired comparisons between peak and post-cooking conditions showed that particle concentrations decreased after cooking. This reduction was statistically significant for ELPI measurements in the

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kitchen (p = 0.00069) and SMPS measurements (p = 0.0015). CPC measurements in the master bedroom also showed a statistically significant reduction (p = 0.031), while CPC measurements outside the bathroom did not show a statistically significant change (p = 0.363), indicating greater variability at that location. A comparison between experiments conducted with and without the extraction fan showed a clear effect of ventilation. Peak concentrations were consistently higher in the absence of ventilation. This difference was statistically significant for CPC bathroom measurements (p = 0.014), ELPI measurements (p = 0.049) and SMPS measurements (p = 0.012). CPC measurements in the master bedroom showed a similar trend but did not reach statistical significance (p = 0.093), likely due to variability in aerosol transport and mixing. No statistically significant change in particle size distribution was observed. The geometric mean diameter (GMD) measured by the SMPS+C did not differ significantly between conditions (42.9 nm without fan and 31.9 nm with fan), indicating that ventilation primarily reduced particle concentration rather than altering particle size. This behaviour is consistent with previous studies demonstrating that ventilation acts predominantly as a dilution mechanism with limited influence on particle size distribution [16].

Stir-fry cooking generated substantial indoor aerosol emissions, with rapid increases in particle concentration observed shortly after the addition of oil and during the cooking of chicken, vegetables, soya sauce, and noodles (Fig. 4). Unlike deep frying, stir-fry cooking involved a sequence of separate cooking stages, resulting in a more complex temporal emission profile with multiple peaks associated with ingredient addition and active heating [11], [31]. The temporal evolution of particle concentration across all instruments (Fig. 4) showed that strong increases in particle concentration were observed during active cooking, with multiple peaks corresponding to different stages of the stir-fry process.

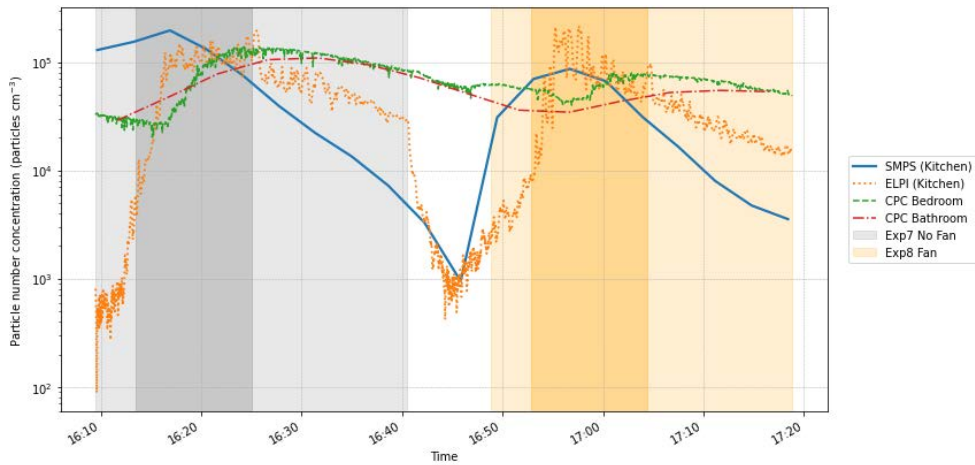

Figure 4: Time-resolved particle number concentration measured during stir-fry cooking experiments conducted without the extraction fan (Exp 7) and with the fan operating (Exp 8). Light shading indicates the duration of each experiment, and darker shading represents the active cooking period.

In the kitchen, the SMPS recorded peak concentrations ranging from 9.13×10^4 to 2.58×10^5 particles cm^{-3}, corresponding to a mean concentration of $(1.08 \pm 0.70) \times 10^5$ particles

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cm^{-3}. This indicates that the use of the extraction fan reduced particle accumulation near the source. The ELPI, positioned at floor level, also recorded strong emissions during both experiments, with peak concentrations of 1.97×10^5 particles cm^{-3} without the fan and 2.17×10^5 particles cm^{-3} with the fan. Unlike the SMPS, the ELPI did not show a reduction in peak concentration in the fan-assisted experiment. This difference likely reflects the ELPI's faster temporal response, sensitivity to a wider particle size range, and its location at floor level, where particle growth and settling processes may differ from those at breathing height. During the experiment without the extraction fan, CPC measurements showed peak concentrations of 1.20×10^5 particles cm^{-3} outside the bathroom and 1.40×10^5 particles cm^{-3} in the master bedroom. With the fan operating, these peaks were lower, at 5.81×10^4 particles cm^{-3} and 8.13×10^4 particles cm^{-3}, respectively. This indicates that the extraction fan reduced aerosol transport to upper-floor locations. In both experiments, the CPC in the master bedroom recorded higher peak concentrations than the CPC outside the bathroom suggesting that aerosol transport within the building was influenced by airflow pathways, including stairwells and room connectivity, leading to non-uniform distribution of particles across the upper floor. Mass concentration measurements obtained using the DustTrak DRX further demonstrated the intensity of emissions during stir-fry cooking. Rapid increases in $PM_{2.5}$ were observed during active cooking stages, particularly during oil heating and ingredient addition. Peak $PM_{2.5}$ concentrations exceeded ~1300 $\mu g\ m^{-3}$, indicating substantial formation of condensable organic aerosol at high temperatures. The DRX measurements showed differences compared with SMPS+C and ELPI observations. These differences are attributed to both measurement principle and sampling height. While SMPS+C and ELPI measure particle number concentration, the DRX measures particle mass, which is more strongly influenced by larger particles formed through condensation and coagulation. In addition, the DRX was positioned slightly lower than the ELPI, which may influence the local particle size distribution due to gravitational settling and near-surface airflow effects. Although the extraction fan reduced particle number concentrations measured by SMPS+C and CPC, high mass concentrations were still observed during the fan-assisted experiment. This suggests that ventilation reduced particle accumulation but did not fully prevent the formation of particulate mass during active cooking.

The multiple peaks observed in Fig. 4 reflect the staged nature of stir-fry cooking. Each stage, including oil heating and ingredient addition, produced short bursts of particle formation, resulting in a more complex temporal profile compared with deep frying. The stir-fry experiments demonstrate that this cooking method is a strong indoor source of UFP, producing high particle concentrations in the kitchen and substantial exposure in other parts of the building. Stir-fry cooking can lead to significant indoor aerosol exposure and that ventilation plays an important role in reducing, though not eliminating, aerosol transport within residential environments [32]. In the stir-fry cooking experiments, the extraction fan reduced particle concentrations measured by SMPS+C and CPC, particularly in upper-floor locations. However, the ELPI and DRX measurements did not show a consistent reduction in peak values, highlighting the influence of measurement method, sampling height, and transient emission dynamics.

4 CONCLUSION

Cooking experiments performed within a well instrumented house (SPHERE) provide a simultaneous assessment of aerosol generation at the source and transport to upper-floor environments, while also allow comparison between particle number and particle mass measurements at different heights of the building. The particles generated in kitchens during cooking disperse to the other rooms via airflow pathways, resulting in exposure in spaces

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distant from the original source. In the study, a multi-location (kitchen, bathroom, study room, bedrooms, sitting room) measurement approach enables direct evaluation of spatial exposure variability within the residential environment. The fried cooked meal generated significantly more aerosols with smaller size, at least one order of magnitude larger in number and two-fold smaller in size than the oven cooked meal. Stir-fry cooking generated substantial indoor aerosol emissions, with rapid increases in particle concentration observed shortly after the addition of cooking materials. Deep frying is a strong indoor aerosol source, producing high particle concentrations in the kitchen and a substantial fraction of particles can be transported throughout the building within a short time. Compared with deep frying, stir-fry cooking generated similarly high peak concentrations but with multiple short-duration emission events associated with different cooking stages. Ventilation conditions significantly influenced particle decay rates, with increased air exchange accelerating removal but also altering spatial exposure patterns.

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