Cooking emissions from typical Norwegian meals: basis for advanced exposure studies

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Abstract. Sustainable urban dwellings are built space-efficient, and open-plan kitchens have increasingly become the norm. A study of newer building projects has shown that the kitchen space is in the inner area of the apartment with limited options for forced window airing, leaving the job of removing cooking emissions to the kitchen hood or general ventilation. One of the aims of our study is to measure exposure from actual cooking in modern apartments, as preparations for further advanced studies. To achieve this, particle number concentrations (>0.3 µm) are measured for three typical Norwegian meals with different ventilation rates at three locations in the kitchen lab. The kitchen setup is comparable to the EN 61591:2019 standard with an area of approximately 30 m² and a height of 2.7 m. The measurements show that the meals and cooking procedures developed are reasonably repeatable. Most of the particles are in the range 0.3-2.5 µm. The meal producing the lowest numbers of particles is the vegetarian pasta Bolognese, while taco and fried salmon which required both higher cooking temperature and contained more fat resulted in a much higher number of particles. The peak for particle number concentration was more than 40% lower for the vegetarian meal. Turning on the kitchen hood at medium setting (286 m³/h) drastically reduced the particle number concentrations, however, the Norwegian requirement of 108 m³/h (low) resulted in a 58% reduction for the taco meal.

Keywords. Kitchen ventilation, cooking emissions, indoor air quality, particulate matter, particle size distribution
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1. Introduction

Indoor air quality (IAQ) is important to both personal health and well-being. During the Covid-19 pandemic, IAQ is of even greater significance as most people are spending a larger amount of their time at home. Moreover, urban dwellings are currently built more energy and space-efficient. This results in more compact and airtight apartments and open plan kitchen and living room solutions are becoming more common.

Cooking is considered one of the main sources of indoor pollutants. The magnitude of cooking emissions will vary depending on the type of food, cooking method, cooking temperature or the cooktop [1–3]. In Norway, electric cooktops dominate the market, either ceramics or induction, which, unlike gas stoves, do not generate emissions. Exposure to cooking fuels is less of an issue in developed countries, but studies have shown that cooking poses a significant health risk due to exposure to particulate matter (ultrafine, $PM_{2.5}$) and polycyclic aromatic hydrocarbons (PAH)[4–6]. The kitchen space is frequently placed in the inner area of the apartment with limited options for forced window airing, thus leaving the job of removing cooking emissions, odour and moisture to the kitchen hood or general ventilation.

The requirement for ventilation rates by the kitchen hood varies between countries. ASHRAE has a requirement of 180 m³/h, while the extract rates by the kitchen hood in the European and Nordic countries range between 72-140 m³/h. The minimum requirement for basic kitchen ventilation rate according to the Norwegian technical building regulations (TEK17) is 36 m³/h, with a minimum additional forced extract rate of 108 m³/h. Studies have shown that the TEK17 standard kitchen ventilation requirements in Norway may not be sufficient to reduce particle emissions generated by cooking [5,7].

Currently, there is a growing demand from the building industry in Norway for more knowledge about ventilation solutions for urban dwellings. Existing laboratory test standards for kitchen hoods are rather simple and not representative of actual cooking routines in modern apartments. In this study, we aim to measure exposure from cooking typical Norwegian meals under controlled ventilation conditions to formulate the basis for more advanced exposure studies. In this paper, three typical Norwegian meals were cooked under different ventilation scenarios, and the exposure at different locations in the kitchen laboratory will be explored.

2. Materials and methods

2.1 Laboratory facilities

All experiments are performed under controlled ventilation conditions in a test room with a height of 2.7 m, a width of 6.2 m, a depth of 4.8 m and a total volume of 80.4 m^3. The kitchen lab, as shown in Fig.1, is larger than the test rooms mentioned in EN 61591:2019 standard for kitchen test facilities, but the kitchen setup is comparable to this standard.

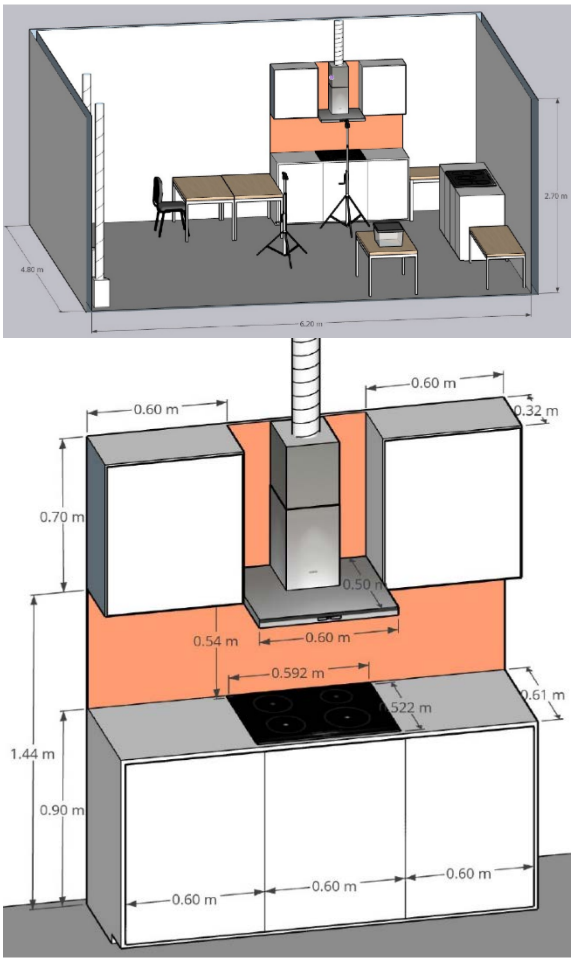

Fig. 1 - Upper: Kitchen lab dimensions and layout. Lower: Kitchen setup.

An individual balanced ventilation system for control of the supply and extract air was installed in the test room, and the supply air was filtered using a HEPA filter. The general exhaust was mounted in the ceiling and was regulated externally using a fan connected to the exhaust duct. The built-in hood fan can operate at four different airflow rates (183, 286, 362, 496 m^3/h) and could also be regulated externally. The flow rates were measured and recorded by an air handling controller DPT-CTRL 2500-D (HK instruments, Finland). Additionally, two different air diffusers were placed on the floor on each side of the entrance door to simulate a realistic apartment system with cascade ventilation and transfer of air from other rooms (e.g. bedroom).

2.2 Kitchen hood and cooktop

A Siemens induction cooktop with four cooking zones, of which two with Ø 18cm (left front and left back zone), one with Ø 14.5 cm (right back) and one with Ø 21 cm (right front). The cooktop has 9 main power levels and one boost function. A standard wall mounted kitchen hood from Siemens is used in the experiments which can operate at both exhaust and recirculation mode. In this study, only the exhaust mode was chosen. The kitchen hood is placed at 54 cm above the cooktop, at the same height as the cupboards.

2.3 Measurement instruments

Particle size distribution was measured using an AeroTrak Handheld particle counter 9303 (TSI Incorporated, USA), calibrated with NIST traceable PSL spheres. It measures particles in the size range of 0.3 – 25 μm and can report up to three channels simultaneously. The AeroTrak has a counting efficiency of 50% at 0.3 μm and 100% for particles >0.45 μm. The AeroTraks were placed in three locations in the kitchen lab (see Fig. 2). Location 1 is assumed to be at the breathing height of an average Norwegian person while cooking and is set to 154 cm above the floor (assuming the mouth is 20 cm lower than the total height), and 50 cm away from the cooktop. Measurement location 2 is chosen to be in the middle of the room and set to 125 cm above the floor. Measurement location 3 is assumed to be the dining location in the kitchen lab. The instrument is therefore placed at a height of 110 cm, which is assumed to be at the breathing height of a sitting person.

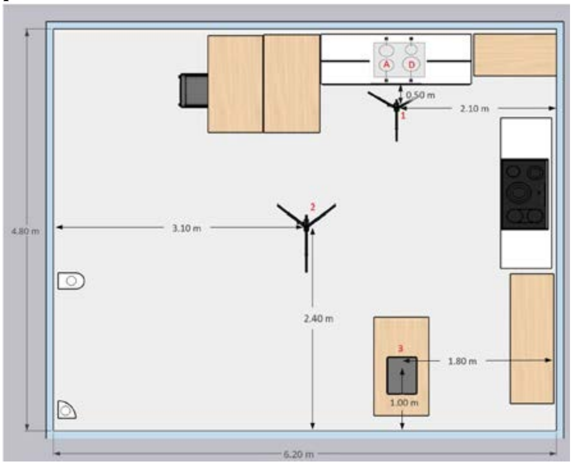

Fig. 2 - Measurement locations.

$PM_{2.5}$ mass concentration was also measured in location 2, using a GRIMM Portable dust monitor

1.108. It measures particles with diameters between 0.3-20 µm and classifies them into 15 size bins. The GRIMM has a reproducibility of ±3%. Measurements were logged at 1-minute intervals. Particle number concentration was converted to mass concentration for GRIMM, using the factory preset particle density of 1.65 kg/m^3 and a c- factor of 1 [8]. Whether this conversion is representative of the particles generated from cooking has not been investigated in this study. A further investigation considering the effect of this choice should be performed in future. Calibration factors have been provided for different meals by O'Leary et al. [9]. However, the kind/type of cooked meals and the equipment used for the preparation in our study are not directly comparable with their work.

Temperature and relative humidity in the kitchen lab were monitored every minute using a Rotronic CP 11 (Rotronic AG, Bassersdorf, Switzerland) with a declared accuracy of ±2.5%RH. In addition, a HIOKI data logger (Hioki EE corporation, Japan) also logged the temperature in the frying pan with thermocouple type K, and in the supply and exhaust air and the test hall next to the kitchen lab with thermocouple type T.

2.4 Test meals and cooking procedure

A review of potential test meals and cooking procedures were done, but relevant studies deviate from assumed typical Norwegian meals. Thus, a precursor survey of Norwegian cooking habits was performed to compose representative meals for this study. As the experiments need to be as reproducible as possible, the meals were simplified, and precise cooking procedures were developed. In short, both meal 1 involved frying and boiling, while meal 3 only frying. The detailed cooking procedure is available in [10]. The kitchen lab is assumed to be a living space for 2 adults. The portion sizes are therefore assumed to be for 2 adults and of relevant nutrition. A list of the meals selected for this study is given in table 1.

Table 1 Selected test meals.

Meal	Contains	Ingredients
1	Minced meat with taco spice 3 repetitions 16 minutes	• Minced meat, 400 g • Taco spice mix, 25 g • Rapeseed oil, 15 ml • Water, 150 ml
2	Vegetarian pasta Bolognese 3 repetitions 13 minutes	• Dried durum wheat spaghetti, 250 g • Pasta Bolognese sauce, 500g • Soya mince, 300 g • Rapeseed oil, 15 ml • Salt, 10 g • Water, 2 litres
3	Fried salmon with wok vegetables 3 repetitions 13 minutes	• Salmon, 400 g • Whole Grain Rice & Vegetable mix, 500 g • Rapeseed oil, 15 ml • Salt, 1 g • Pepper, 1 g

The nutritional value per 100 g for each of the meals is listed in table 2.

Table 2 Nutritional content of each test meal per 100g.

Nutritional value for each meal per 100 g	Minced meat with taco spice	Vegetarian pasta Bolognese	Fried salmon w/wok vegetables
Energy	866kJ/ 206kcal	623kJ/ 147kcal	656 kJ/ 157kcal
Fat	13.5	1.4	7.7
(saturated), [g]	(5.9)	(0.2)	(1.4)
Carbohydrates	3.1	23.5	10.6
(sugars), [g]	(0.9)	(4.7)	(1)
Fiber, [g]	0.01	3.04	1.44
Protein [g]	17.5	8.6	10.7
Salt [g]	2	0.8	0.4

2.5 Experimental setup

Table 3 shows an overview of all the experiments, the table is color coded to illustrate similar scenarios. Tests were performed for two ventilation scenarios: (1) with the kitchen hood off and a basic ventilation airflow rate of 72 m^3/h, (2) with the kitchen hood on setting 2 and thus achieving an airflow rate of 322 m^3/h (a basic ventilation airflow rate of 36 m^3/h plus kitchen hood extract of 286 m^3/h). Full mixing conditions were assumed. All experiments were repeated 3 times to ensure reproducibility and all experiments were logged for 1 hour.

Table 3 Overview of the experimental setup. Each experiment was repeated three times.

Exp. nr	Cooking duration (min)	Ventilation rate; Base+extract (m^3/h)	Duration of kitchen hood on (min)
Meal 1-1	16	72 + 0	0
Meal 1-2	16	36 + 286	60
Meal 1-3	16	36 + 286	16
Meal 1-4	16	36 + 286	55
Meal 1-5	16	36 + 108	60
Meal 2-1	13	72 + 0	0
Meal 2-2	13	36 + 286	60
Meal 3-1	13	72 + 0	0
Meal 3-2	13	36 + 286	60

The kitchen hood was turned on as the cooking started and kept on till the end of the measurement period. The results have been corrected for the difference in the basic ventilation rate when the kitchen hood is on (36 m^3/h) and off (72 m^3/h). The particle counts for the kitchen hood was off were multiplied by two to account for the different in the basic ventilation rate.

Three additional tests were also done to test different kitchen ventilation usage patterns. Due to time constraints, these tests were only done for meal 1 – taco. The purpose for these tests was to assess the effect of varying the duration of the use of the kitchen hood (1) by turning off the fan immediately after the cooking was done – exp. nr 1-3, (2) by turning on the fan 5 minutes after the cooking had started – exp. nr 1-4 and (3) the pollutant level at reduced extract rates using the minimum required kitchen ventilation in Norway (exp. nr 1-5; 36 + 108 m^3/h).

3. Results and discussion

3.1 Temperature and relative humidity

The room temperature in the kitchen lab during the experimental period was rather stable and varied between 21.4 - 23.9 °C. The relative humidity (RH) varied between the different test meals and fluctuated between 12.4 to 57.1%, particularly during meal 2 (vegetarian pasta bolognese) where boiling was involved, and the kitchen hood was turned off (RH>48.5%). An overview of the measured temperature and relative humidity in the kitchen lab during the different experiments is provided in Appendix A.

The temperature in the pan was measured with a thermocouple connected to a piece of aluminum. The calibration with only oil was very accurate to the actual temperature measured with the infrared thermometer. These preliminary experiments also revealed what power settings to use for stable pan temperature.

3.2 Instrument comparison

To ensure comparable result the particle number count of the GRIMM and Aerotrak was compared to see similarities in particle number count and the reproducibility of the repetitions for each test. Both the GRIMM and Aerotrak were placed in location 2. A comparison of the measured particle number concentrations over the entire size range (>0.3 µm) was done regardless of the differences in the cut-off diameter of the instruments. Fig. 3 shows the particle number concentrations of frying salmon with the kitchen hood off. Generally, the particle number concentrations obtained by Aerotrak are somewhat higher than the ones measured by the GRIMM. This is most likely due to the larger size range measured by the Aerotrak.

Scatterplot of each measurement series by the two instruments were plotted against each other and resulted in an average regression coefficient (R^2) of 0.84 when the kitchen hood was turned off indicating a good agreement of measured particle number concentrations by the two instruments.

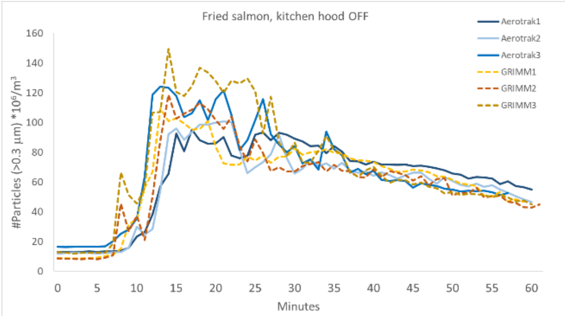

Fig. 3 - Particle counts as measured by GRIMM and AeroTrak at location 2 (middle of the room) cooking meal 3 – fried salmon when the kitchen hood was turned off.

A comparison of the three repetitions was also done and resulted in an average regression coefficient of 0.79 for GRIMM and 0.72 for Aerotrak. As seen in Fig. 3, there are variations in the magnitude of the particle number concentrations which could be due to insufficient airing in between each experiment. Moreover, due to time constraints, the experiments of the same test meal were not always done on the same day. However, the temporal trends are somewhat consistent. We simplified the cooking procedure to ensure the reproducibility of the outcome of the experiments. Each ingredient was also measured in advance, but cooking is a complicated process, and it is challenging to ensure that every movement is done the same way each time [1]. Between each experiment, the kitchen lab was ventilated well for 1.5h. Nevertheless, the three repetitions of making each meal are considered comparable enough, thus the remaining results are reported as an average of the three repetitions.

3.3 Effect of kitchen hood

For all meals, on average, more than 98% of the particles emitted were in the size fraction 0.3-2.5 µm, which is in agreement with previous research [2]. Figure 4 shows the average particle number concentrations for three different size distributions measured for 1h at the breathing height of the cook. The cooking duration is 16 minutes for meal 1 and 13 minutes for meal 2 and meal 3.

For meal 1 - taco and meal 3 – fried salmon, the number of particles increases rapidly in the beginning which corresponds to the rise of pan temperature. Both meals also yielded the highest peak particle number concentrations for all size fractions, resulting in the highest exposure for the cook when the kitchen hood is not turned on.

These two meals also have the highest content of saturated fat, confirming the positive correlations between fat content and emissions rates. This is in line with previous findings [3,11]. Also, high cooking temperature results in increased emissions of particles, which is in line with our results as salmon were fried with the highest pan temperature out of all three meals.

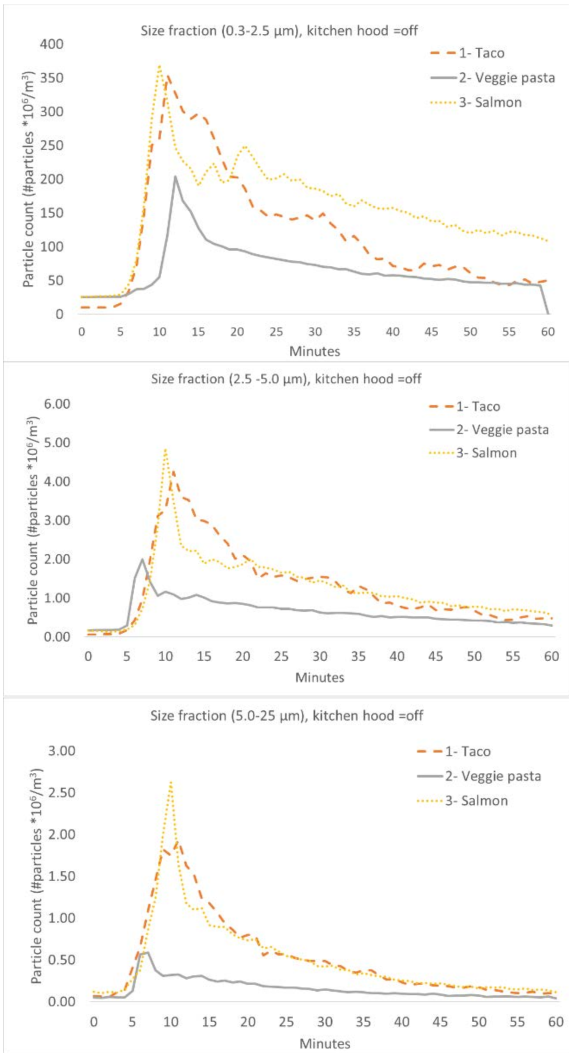

Fig. 4 - Particle counts for the three test meals with the kitchen hood off according to different size fractions. Measurement location=breathing height of the cook. Note the different scale on the y-axis.

In comparison, the peak particle number concentrations for vegetarian pasta Bolognese were much lower. Fig. 4 shows an initial increase of the larger size fractions due to the boiling of water. The increase of the smaller size fractions happens around 10 minutes when tomato sauce is added. For the other two meals, the increase in particle counts occurs simultaneously for all three size fractions. As seen in fig. 5, particles in the smaller size fractions do not decrease to the initial levels after one hour when the kitchen hood is turned off and with a base ventilation rate of 72 m³/h.

Turning on the kitchen hood drastically reduced the particle number concentration for all three meals. Fig. 5 shows the particle number concentration for the smallest size fraction (0.3-2.5 µm) as most of the particles emitted are in that size fraction. Meal 1-taco resulted in the highest peak concentration (16.6·10⁶/m³) followed by salmon (15.7·10⁶/m³) and veggie pasta (11.9·10⁶/m³), lowered from a level of above 360·10⁶/m³ for taco and salmon meals.

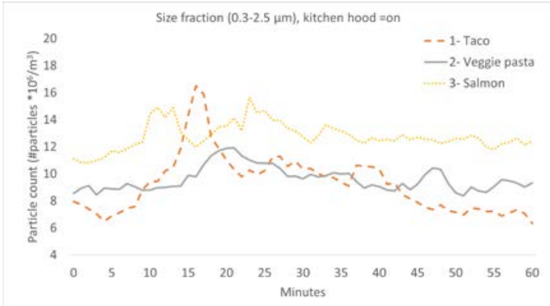

Fig. 5 - Particle counts for the smallest size fraction 0.3-2.5 µm (average values) for the three test meals with the kitchen hood on medium setting (36+286 m³/h). Measurement location =breathing height of the cook.

Fig. 6 shows the average particle number concentrations for all size fractions (>0.3 µm) at different ventilation rates measured while cooking meal 1- taco. With the kitchen hood turned on using the minimum requirement for forced ventilation in Norway (108 m³/h), the highest average peak particle number concentration was 152·10⁶/m³, resulting in a 58% peak reduction compared to when the kitchen hood was turned off. This indicates that the minimum requirement might not be sufficient to reduce the emissions from frying meat with taco spices and is also assumed to be the case for fried salmon.

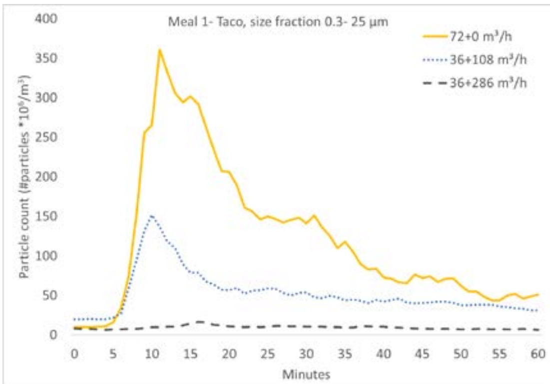

Fig. 6 - Particle counts for all size fractions 0.3-25 µm (averaged) for meal 1 - taco at different ventilation rates. Measurement location =breathing height of the cook. The cooking time is 16 minutes.

3.4 Exposure at different locations

Due to more open living room and kitchen solutions, we also assess exposure at different locations in the kitchen lab. Fig. 7 shows the particle number concentration for all size fractions for meal 1 - taco at the three measured locations with the kitchen. When the kitchen hood is off, the peak particle number concentration decreases with distance from the cooktop, a reduction of almost 50% from location 1 to location 3 (Table 4, exp 1-1, taco). The peak around 16 minutes at location 3 is when the dish was moved to the dining area.

When the kitchen hood is turned on, there are generally smaller differences in peak particle number concentrations and the 1h-averaged particle number concentrations at the different locations. For these experiments, the kitchen hood was on for the entire measurement duration of 1h.

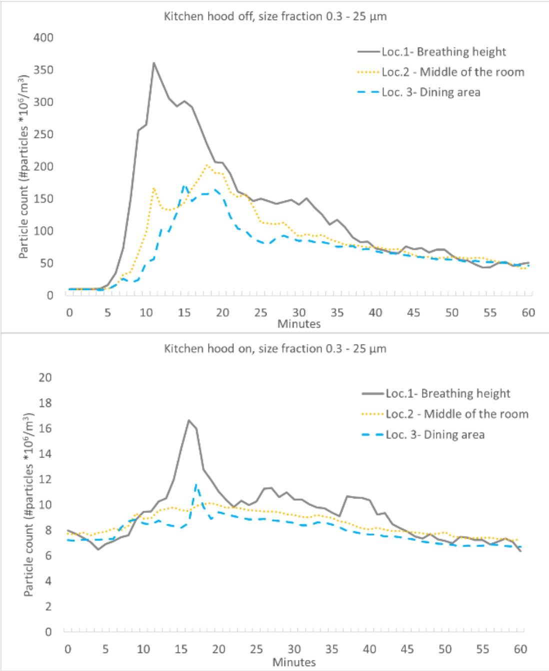

Fig. 7 - Particle number concentration (0.3-25 µm) for Meal 1-taco in all three locations (upper with the kitchen hood off, lower with the kitchen hood on).

Table 4 shows the peak particle number concentrations and average particle counts for the duration of 1h for all three meals.

Table 4 Peak particle number and 1-h average concentration of particle number for all size fractions for different test meals at three locations. Loc 1=breathing height, loc.2 =middle of the room, loc 3= dining area.

Exp.	Peak ($10^6/m^3$)			1-h average ($10^6/m^3$)		
	Loc. 1	Loc. 2	Loc.3	Loc. 1	Loc. 2	Loc.3
1-1	360.6	202.6	174.4	121.8	85.3	71.3
1-2	16.6	10.1	11.7	9.3	8.5	8.0
1-5	152	52	40	53	30	21
2-1	205.1	117.6	98.0	65.5	60.8	51.4
2-2	11.9	9.7	9.4	9.6	8.9	8.2
3-1	377.0	208.0	179.9	162.5	127.5	106.1
3-2	15.7	13.1	16.0	12.8	12.6	11.8

The trends for the other two meals (2-1, 3-1) are similar, with the highest exposure at the cooking area, and lower in the other areas in the kitchen lab when the kitchen hood is turned off. With the kitchen hood turned on (286 m^3/h), there are small differences in the particle number concentrations at the different locations in the kitchen lab. This indicates that cooking emissions are mitigated by the kitchen hood and does not influence the exposure in the rest of the room. An extract rate of 108 m^3/h (exp. 1-5) results in lower emissions, but not sufficiently compared to 286 m^3/h.

3.5 Hood usage pattern and emissions

A preliminary survey was performed to map the typical usage of the kitchen hood and other habits during cooking. It was found that more than 30% of the respondents did not always turn on the kitchen hood while cooking [10]. Noise and forgetting to turn it on were some of the reasons given, in addition, the usage of the kitchen hood was also depending on the type of food cooked or preparation method. Moreover, most people turn off the kitchen hood immediately after cooking. Based on these findings, we performed some additional experiments to assess the effect of kitchen hood usage patterns on particle emissions.

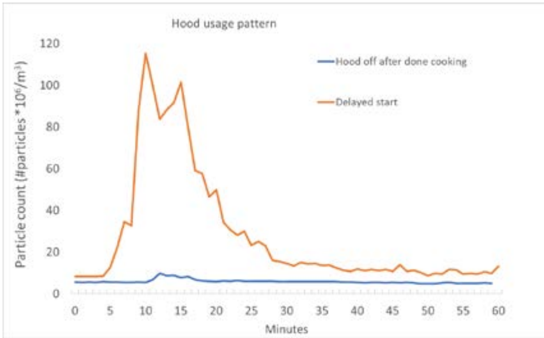

Fig. 8 - Particle counts for all size fractions for meal 1-taco with different hood usage patterns.

Fig. 8 shows that forgetting to turn on the kitchen hood when cooking by 5 minutes has a considerable effect on the number of emitted particles. Previous studies [10,13] have shown that some people might forget to turn on the kitchen fan or turn it off immediately due to the noise. In comparison, turning off the kitchen hood immediately after cooking versus leaving it on after cooking has little effect. This corresponds also with Fig. 6, showing that keeping the hood on for a long time after the cooking has ended does not make any difference in lowering the exposure level. This is in line also with the results from a study in the USA [12].

Our findings indicate that turning on the kitchen hood when the cooking starts or increasing the ventilation rate is a much better measure than leaving the kitchen hood on after the cooking has ended. Particles must be captured when generated.

3.6 Particle mass concentration

Particle mass concentration was only measured in the middle of the room (see Fig. 9), converted from the particle number concentrations measured by the GRIMM. When the kitchen hood is turned off, the highest $PM_{2.5}$ peak concentration was from meal 1-taco (84.9 µg/m³), while the lowest was from meal 2 – vegetarian pasta bolognese (43.7 µg/m³). When the kitchen hood was turned on, the measured $PM_{2.5}$

mass concentrations were lower than 2 µg/m^3 for all three meals. The particle mass concentrations show similar trends as the particle counts.

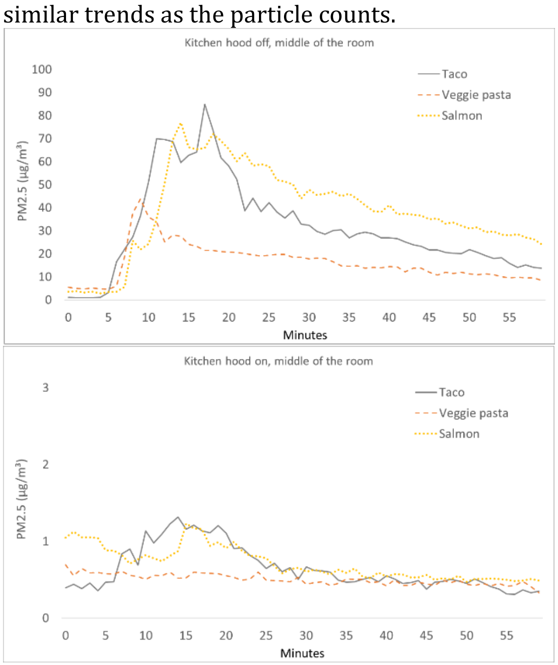

Fig. 9 - PM$_{2.5}$ mass concentrations measured in the middle of the room, for the three different meals. Upper: with kitchen hood off, and lower: with the kitchen hood on.

4. Conclusions

Particle number concentrations are measured for three typical Norwegian meals with different ventilation rates at three locations in the kitchen lab. The measurements show that the meals and cooking procedures developed are reasonable repeatable. Most of the particles are in the size range 0.3-2.5 µm.

The meal producing the lowest numbers of particles is the vegetarian pasta Bolognese, while the taco and fish meals which required both higher cooking temperature and contained more fat resulted in a much higher number of particles. The peak for particle number concentration was more than 40% lower for the vegetarian meal when the kitchen hood was turned off.

Turning on the kitchen hood at medium setting (286 m^3/h) drastically reduced the particle number concentrations, however, the Norwegian requirement of 108 m^3/h (low) reduced the number of particles at the breathing zone of the cook by only 58% for the taco meal.

Our experiments show that keeping the kitchen hood on after cooking has ended had minimal effect on the exposure, while a 5 min delay in turning on the kitchen hood resulted in an exposure level similar to the kitchen hood on a low setting. For open-plan kitchen solutions, the usage of the kitchen hood will impact the exposure of the occupants. Particles must be captured when generated.

5. Acknowledgements

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The datasets generated and analysed during the current study are not publicly available because the datasets are in Norwegian and are part of an initial study but will be available by personal request.

Appendix A

Table A1 Measured average (minimum; maximum) relative humidity and temperature in the lab kitchen during the individual experiments. Measurement time=1h.

Test meal	Extract flowrate	Relative humidity (%)	Temperature (°C)
1-1	Off	27.2 (25.2; 30.5)	22.4 (22.2; 22.5)
		17.2 (15.2; 21.2)	21.5 (21.4; 21.6)
		17.4 (15; 21.7)	21.7 (21.6; 21.8)
1-2	On	12.7 (12.4; 13.2)	21.7 (21.4; 21.8)
		39.2 (37.5; 40.3)	22.6 (22.5; 22.7)
		37.1 (36.4; 37.8)	22.8 (22.7; 22.8)
1-3	On	39.7 (39.3; 40.2)	22.7 (22.6; 22.8)
		27.3 (26.5; 29.3)	22.4 (22.3; 22.4)
		20.9 (20; 21.9)	22.3 (22; 22.4)
1-4	On	40.1 (39.1; 40.6)	22.6 (22.5; 22.7)
		28.3 (26.7; 32.7)	23.8 (23.6; 23.9)
		27.6 (26.6; 30.1)	23.7 (23.6; 23.9)
1-5	On	40.4 (38.1; 42.9)	23.2 (23.1; 23.3)
		44.5 (43.6; 45.8)	23.3 (23.1; 23.4)
		43.9 (40.2; 48.2)	23.5 (23.4; 23.6)
2-1	Off	50.6 (39.5; 55.8)	23.2 (22.9; 23.3)
		52.7 (43.3; 57.1)	23.3 (23; 23.4)
		48.5 (43; 53.9)	23.4 (23.1; 23.6)
2-2	On	37.4 (37; 38)	22.9 (22.8; 22.9)
		36.6 (36.1; 37.5)	23 (22.8; 23.1)

		36.9 (36.5; 38.1)	23.1 (23; 23.1)
3-1	Off	37.2 (36.3; 38.3)	23.1 (22.9; 23.3)
		36.8 (35.3; 37.9)	22.6 (22.2; 22.7)
		37.6 (36.8; 38.8)	22.4 (22; 22.6)
3-2	On	41.3 (40.8; 41.6)	23.3 (23.2; 23.3)
		42 (41.4; 42.7)	23.4 (23.3; 23.5)
		43 (42.7; 43.6)	23.5 (23.3; 23.6)

6. References

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