On-Site Capture Efficiency of Kitchen Range Hood Based on Particle Diameters and Exhaust Flow Rates

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ABSTRACT

Particles generated from cooking activities are the biggest contributor to the concentration of indoor particles in most homes, and they are not easily removed without natural or mechanical ventilation. As more focus is directed on human health, kitchen range hoods have drawn increasing attention and their performance in various conditions needs to be evaluated. Consequently, in this study, we performed measurements to establish the particle capture efficiency of a kitchen range hood for various particle diameters at different exhaust flow rates. The kitchen particle concentration generated by bacon-frying was measured while maintaining the differential pressure of the kitchen and adjacent zone at 0–1 Pa through the supply of outdoor air. Since the supply fan had no filter and the walls of the of the testbed were not sufficiently airtight, which is as same as typical dwellings, so an estimation of the particle concentration from the supply air or penetrated air had to be subtracted from the measured concentrations, to establish the concentration generated from bacon-frying alone. Within the particle diameter range of 0.3–10 μm, smaller particles with higher kitchen hood exhaust rate generally exhibited better capture efficiencies. Although the capture efficiencies at both exhaust rates (250 m^3/h and 350 m^3/h) were almost identical for similar particle diameters, (except for the 10 μm), the peak concentration and the time taken returning to the background concentration were reduced at an exhaust rate of 350 m^3/h.

KEYWORDS

Capture efficiency, Kitchen range hood, Particulate matter

1 INTRODUCTION

Cooking is one of the biggest contributors to indoor particle concentration, increasing it by as much as 60 times during cooking (Kwon et al., 2013). Moreover, as building envelopes have become increasingly airtight, the generated particles are not easily removed without natural or mechanical ventilation. Consequently, range hoods, which directly and effectively remove the particles generated during cooking activities, have become an essential kitchen accessory. With the wide array of range hoods available on the market, the evaluation of hood performance has become an important issue. Several studies have been conducted evaluating the performance of hoods in various conditions using gas (SF_6, CO_2, etc.) or particles.

Particles of diverse sizes are generated during cooking. For example, turning on a gas stove generates ultra-fine particles (UFPs), sautéing generates coarse particles, and frying generates both (Abt et al., 2000). Different particle sizes exhibit different behavioral properties, and a hood's capture efficiency (CE) differs for fine and coarse particles. Several studies related to particle-capture efficiency have focused on UFPs (Lunden et al., 2015; Singer et al., 2012). However, the evaluation of hood performance on coarse particles is also needed, as pan frying and sautéing are common cooking methods.

The exhaust rate of kitchen range hoods is another important factor related to the reduction of particle concentration during cooking. In general, the higher the exhaust rate, the more effective the hood's air pollutant removal. However, this is only true if lower rates are inadequate: if particles can be sufficiently removed at lower exhaust rates, the use of higher exhaust rates might be unnecessary, and using lower rates can conserve energy and minimize noise. Accordingly, in this study, we analyze the CE of kitchen range hoods based on particle size and hood exhaust rate.

The goal of this study is therefore to compare the performance of kitchen range hoods by calculating the CE during performance tests using various particle diameters, ranging from 0.3–10 µm, and two different kitchen range hood exhaust rates, 250 m^3/h and 350 m^3/h.

2 MATERIAL AND METHODS

2.1 Testbed

The experiments were conducted in a testbed in Seoul over about two months in January 2020. The testbed consisted of a kitchen and two adjacent rooms, as shown in Figure 1. The dimensions of the kitchen were 3.35 × 2.5 × 2.4 m^3 (width × length × height), respectively, and the volume was 20.1 m^3. A U-shaped kitchen counter, sink, chimney type range hood, and highlight cooktop, and two cabinets, were installed in the kitchen. The kitchen range hood was mounted between the two cabinets, 60 cm above the cooktop. The exhaust air flow rate of the range hood was monitored using an air flow capture hood (420, Testo). The kitchen range hood (90 cm × 55 cm) was larger than the cooktop (60 cm × 51 cm). The cooktop power consumption was 220 Wh/kg. It had two medium-sized burners on the front and back on the left side, and one large-sized burner in the middle on the right side. We used the front medium-sized burner for cooking in this study.

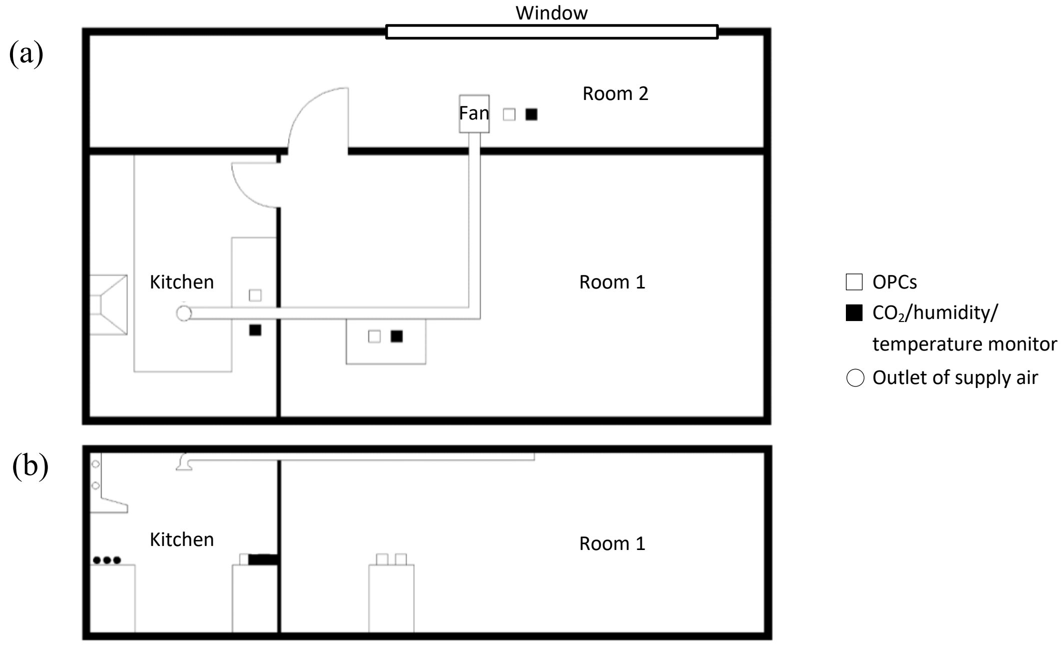

Figure 1: (a) Schematic floor plan and (b) cross-section of the testbed.
Ductwork connected a fan located in room 2 with the kitchen.

Furthermore, in the testbed, there was a large window which was always kept opened, as well as a fan with no filter in room 2. Ductwork connected the fan to the kitchen to provide make-up air when operating the kitchen range hood and maintain the differential pressure between the kitchen and room 1 near zero. However, there was a construction site approximately 30 m away from the testbed, resulting in a high particle concentration in room 2. Consequently, it was expected that some of the particles from construction were delivered to the kitchen via the fan and the ductwork. Hence, the pressure of the kitchen was maintained at 0–1 Pa when the two doors (the kitchen and room) were closed during the experiments. The differential pressure of the kitchen and the room was monitored using a multifunction transmitter which had differential manometer functions (C310, Kimo).

2.2 Particulate Matter Measurement

Optical particle counters (OPCs) were placed in the kitchen and room 2, one for each zone. The OPCs used in these experiments (Aerotrak-9306, TSI Incorporated) measured particle sizes ranging from 0.3–25 μm with six channel sizes of 0.3, 0.5, 1, 3, 5, and 10 μm, respectively, at a flow rate of 2.83 L/min. The size resolution was less than 15% at 0.5 μm, and the counting efficiency was 50% at 0.3 μm. The sampling rate was set at 1 min.

2.3 Cooking Procedure

Bacon was chosen with the expectation that it would generate a similar number of particles for each cooking experiment, because of its even size, weight, and even distribution of fat. The weight of each piece of bacon was measured before every experimental case, and each piece was approximately 40 g. The bacon-frying procedure was as follows. First, the hood was turned on (or kept off, depending on the experiment). Then the pan was preheated until the surface temperature reached 210–230 °C, which took about 3 minutes. Next, the bacon was cooked for 3 minutes, turned over and cooked for another 2 minutes. Lastly, the pan was covered with a lid and removed from the testbed through room 2, with the kitchen door being closed immediately. The purpose of the removal of the particle source (bacon and pan) was to prevent further particle generation. After an interval, when the particle concentration returned to the original background concentration, the testbed was ventilated and wiped with wet tissue to remove any oil and particles attached to the walls, cooktop, and kitchen range hood. All doors were closed during experiments with the hood switched on. The experiment was repeated twice for the 'hood off' case and three times each for the range hood exhaust rates of 250 m^3/h and 350 m^3/h. In the 'hood on' cases, the hood remained turned on at the same exhaust rates until the kitchen returned to the original background concentration.

2.4 Calculation of Air Change Rate

CO_2 concentration, humidity, and the temperature of the kitchen were measured using a CO_2/humidity/temperature monitor (MCH-383SD, Lutron Electronic). The air change rate per hour (ACH) of the kitchen when the fan and the kitchen range hood was not operating was calculated by the tracer gas decay method using CO_2. The equation for calculating the ACH is based on the mass balance equation (Cui et al., 2015):

$$ACH(t) = -\frac{1}{C_{CO2}(t)}\frac{dC_{CO2}(t)}{dt}, \tag{1}$$

where, $C_{CO2}(t)$ is the CO_2 concentration of the kitchen. The calculated average ACH of the kitchen was 0.98/h, which implies low airtightness of the kitchen.

2.5 Calculation of Capture Efficiency

There is a standard test method for measuring capture efficiency of domestic range hoods, which requires tracer gas and measurement of its concentration in the exhaust air of the kitchen range hood. (ASTM E3087-18) Several studies share the equation quoted in this standard for their calculation of CE in experimental or computational fluid dynamics tests (Eom et al., 2023; Kim et al., 2018; Singer et al., 2012).

However, in some circumstances, applying this approach can be difficult since it needs the measurement of the exhaust air of the range hood. This is especially true when using particle concentration to evaluate the on-site CE, owing to the challenging nature of using OPCs to measure concentration in the supply air and the exhaust air inside the kitchen range hood. Consequently, an alternative equation was applied (Lunden et al., 2015):

$$CE = \frac{M_{captured}}{M_{emitted}}. \quad (2)$$

CE is the particulate mass (or number) exhausted through the kitchen range hood (mass captured in the hood, $M_{captured}$) divided by the mass (or number) emitted from the source ($M_{emitted}$). In this study, the number of particles were measured to obtain the CE.

To measure the mass of particles captured by the range hood, the OPC must be inserted into the exhaust duct. Furthermore, the measured particle mass by OPCs could be influenced by the large volumetric flow rate of the kitchen range hood because it does not have steady or calm airflows as the OPCs normally situates. Accordingly, the particle mass captured in the hood was calculated by subtracting the mass that was not captured in the hood but remained in the kitchen from the mass emitted by cooking:

$$M_{captured} = M_{emitted} - M_{remained}. \quad (3)$$

Where $M_{remained}$ is the mass of the pollutant in the kitchen. Substitution of Equation 3 into Equation 2 yields first-pass CE, which is used as a metric of kitchen range hood ability to pull the pollutants originated from the cooktop directly into the range hood before mixing into the indoor air, and this is the same definition and methodology that Singer et al. (2012) and Lunden et al. (2015) followed. In studies of Singer et al. (2012) and Lunden et al. (2015), they measured CO2 concentration inside the exhaust downstream of the range hood so that they can subtract the room CO2 concentration from it to obtain the directly captured pollutant mass and compute the first-pass CE. However, since the use of OPCs in the exhaust hood airstream is limited, the mass that did not captured and remained in the room was subtracted from the $M_{emitted}$, to compute the $M_{captured}$ indirectly.

To establish $M_{emitted}$, we measured the particle concentration in the kitchen during and after cooking with the hood and supply fan turned off. Although the kitchen was maintained at a slightly positive pressure to prevent particle penetration from the outside to the kitchen as much as possible, prior ACH measurements testify to the low airtightness of the walls between the kitchen and rooms. Hence, outside particles penetrated the room and kitchen, resulting in an increase of the kitchen particle concentration, which affected $M_{emitted}$. For $M_{remained}$, the same procedure was used, but with the hood and the supply fan turned on. As stated, the supply fan had no filter and outdoor particles were delivered to the kitchen, resulting also in an increase in $M_{remained}$.

The particle concentration of the kitchen included not only the mass generated from cooking but also the mass coming in from other zones. Moreover, as the particle concentration of the outdoor air fluctuated, so did that of the kitchen. To account for the effects of any outdoor concentration, $M_{emitted}$ and $M_{remained}$ were converted as follows:

$$M_{emitted} = M_{hood\ off} - M_{penetrated}, \tag{4}$$

$$M_{remained} = M_{hood\ on} - M_{supplied}. \tag{5}$$

Here, $M_{hood\ off}$ and $M_{hood\ on}$ are the particle mass in ambient air of the kitchen when the hood was turned off and on, respectively; $M_{penetrated}$ is the penetrated particle mass measured in room 1; and $M_{supplied}$ is the particle mass moved from room 2 to the kitchen via the fan and ductwork.

Among the experimental studies on kitchen range hood performance regarding particulates, there is one study which was conducted in a chamber to prevent the above particulate contamination problem (Lunden et al., 2015). They equipped HEPA filters to their chamber to supply particle-free air so that they could focus only on the particles generated from cooking itself. Another laboratory study (O'Leary et al., 2019) used an HVAC unit equipped with an AFPRO F7 filter to supply air and thus evaluate the hood performance based on particle CE. Alternatively, other researchers (Rim et al., 2012) have suggested using particle reduction effectiveness, which is the ratio between the measured integrated particle concentration with the range hood on and it off, and conducted on-site experiments using this method. It is assumed that the ambient or background concentration was constant in their study. However, since, in the current study, the construction site was nearby, we considered the fluctuation of penetrated or supplied particle concentration.

Equations (2), (3), (4), and (5) can be expressed as follows, by converting mass to concentration:

$$CE = 1 - \frac{V\int_{t0}^{tb}(C_{hood\ on} - C_{supplied})dt}{V\int_{t0}^{tb}(C_{hood\ off} - C_{penetrated})dt}. \tag{6}$$

Where V is the volume of the kitchen. Since the concentrations in equation 6 indicates particle count per unit volume in the kitchen, not in the exhaust duct, so that to obtain the total particle number of the kitchen, total volume has to be multiplied and integrated with the time of measurement. The integral of concentration from the start of the experiment, *t0*, to the time taken to return to the background concentration, *tb*, is required because the mass in equations (1) to (4) refers to the total mass. The background concentration is the estimated concentration of the kitchen that formed due to penetrated or supplied particles ($C_{penetrated}$ and $C_{supplied}$, respectively). *tb* in numerator and denominator is not necessarily same value, because it should represent the mass of the captured and emitted respectively, as stated in the Equation 2, at the end.

The experimental cases and estimated parameters are shown in Table 1.

Table 1: Experimental cases and estimated parameters

Case	Supply Fan	Exhaust Flow Rates	Repeated #	Estimated Parameters	Estimated Concentration
Hood off	Not operated		2	Penetration Coefficient, Deposition Rate	$C_{penetrated}$
Hood on	Operated	250 m³/h 350 m³/h	3 3	Removal Efficiency of the Fan, Deposition rate	$C_{supplied}$

2.6 Calculation of Penetration Coefficient and Deposition Rate

To calculate the mass in the kitchen formed by factors other than emission, $M_{penetrated}$estimation of the penetration coefficient and deposition rate is required. Penetration coefficient (P)is the rate at which the particle penetrates inside, and it can be differ by the shape or roughness of the exterior wall. Deposition rate (K) is the rate of decay due to the sink(deposition) of the particles. Both penetration coefficient and deposition rate are depend on the particle size. If the generation and resuspension of particles is ignored, the particle mass conservation equation can be expressed as follows:

$$\frac{dC_{penetrated}(t)}{dt} = aPC_{room2}(t) - (a+K)C_{penetrated}(t), \tag{7}$$

Where $C_{penetrated}$ is time-varying concentration of the kitchen depend on infiltration and deposition and does not consider the emission. a is the average ACH calculated in section 2.4 and $C_{room2}(t)$ is the time-varying particle mass concentration in room 2.

Rim et al. (2012) suggested a method for approximating $dC(t)$ in linear terms, which is permissible if the time step is relatively small (1 min for this study).

$$C_{penentrated}(t+1) = a(t)PC_{room2}(t)\Delta t + \{1-(a(t)+K)\Delta t\}C_{penetrated}(t) \tag{8}$$

The estimation was based on the data of two repeated experiments conducted six hours after cooking activity when the hood was off.

2.7 Calculation of Removal Efficiency of the Fan and Deposition Rate

$C_{supplied}$ can be calculated using the same method as above, this time substituting a and P for Q/V and $(1\text{-}\varepsilon)$, since any air change occurred mainly through the supply air and hood exhaust as the kitchen environment was maintained at a positive pressure.

$$C_{supplied}(t+1) = (1-\varepsilon)\frac{Q}{V}C_{room2}(t)\Delta t + \{1-\left(\frac{Q}{V}+K\right)\Delta t\}C_{supplied}(t) \tag{10}$$

The estimation was based on data captured 10 minutes after cooking activity when the hood was on.

The penetration coefficient P, deposition rate K, and supply fan removal efficiency ε were approximated by the least squares method, in a way that minimizing the difference between the modeled and actual concentration using a Microsoft Excel solver. When calculating the CE, the background mass ($M_{penetrated}$ and $M_{supplied}$) was estimated and subtracted from the actual particle mass in the kitchen ($C_{hood\ on}$ and $C_{hood\ off}$).

3 RESULTS AND DISCUSSION

3.1 Removal Efficiency of the Fan and Ductwork

The particle removal efficiency of the fan and ductwork (ε) tended to increase as the particulate diameter increased, as shown in Figure 2. The larger the hood exhaust rate, the greater the supply air needed, hence the greater the required fan speed. Nonetheless, the removal efficiency was similar for both exhaust rates, 250 m^3/h and 350 m^3/h. In general, the removal efficiencies at 350 m^3/h were slightly smaller than those at 250 m^3/h for particle sizes 1–10 μm

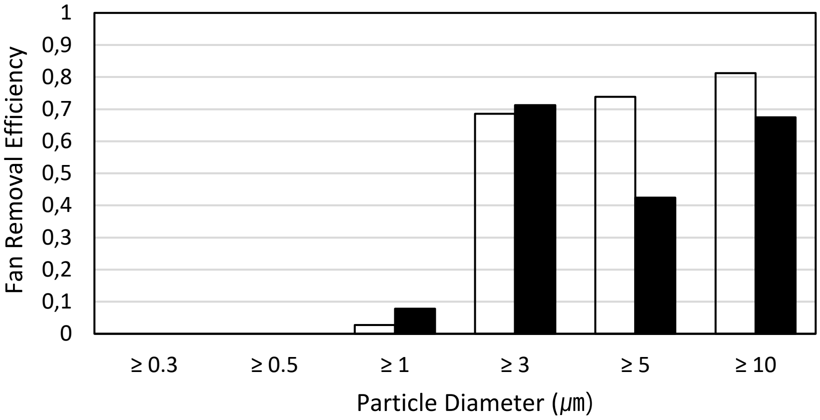

Figure 2: Particle removal efficiency of the fan and ductwork according to particle diameter and exhaust flow rate.

with some minor variations. The removal efficiency was zero for 0.3 µm and 0.5 µm at both exhaust rates.

3.2 Calculated Kitchen Concentration

Figure 3 shows the particle concentration of the kitchen calculated by subtracting the estimated background concentrations (penetrated concentration when the hood was off and supplied concentration when the hood was on) from the measured kitchen concentration to remove the effect of any outdoor concentration infiltrated from other zones (as in equations (4) and (5)). Two hood off repeated experiments display distinctive time-varying concentration patterns from each other, one of them is showing bigger peak concentration throughout the particle size bins, indicating that the emission rates might be different since the penetration coefficient and deposition rate were set to be the same. We attempted to generate same amount of particles throughout the experiments by tightly control cooking protocols, but the fat distribution of the bacon or the degree of cleanliness of the frying pan can be differ by the tests, which leads to failure of the exactly reproducible experiment. For accounting the uncertainty of the mass emitted by cooking, both hood off experiments were accounted when computing the CE.

The 0.3 µm- and 0.5 µm-diameter particles did not settle easily: the time taken for the kitchen to return to the background particle concentration was approximately 10 hours when the hood was off. When the hood was on, it took just 20 minutes for all particle sizes, except for 0.3 µm and 0.5 µm, to return to the background concentration, and this process was faster at 350 m^3/h than at 250 m^3/h. In particular, the particle concentration of 0.3 µm did not increase when the hood was operated at 350 m^3/h. The peak concentration of all particle diameters decreased as the exhaust rate increased.

3.3 Capture Efficiency

The CEs of the range hood for various particle diameters at different exhaust flow rates were calculated for each experimental case (three cases each for the 250 m^3/h and 350 m^3/h flow rates and two for the 'hood off', for a total of eight cases), as shown in Figure 4. Note that $C_{hood\ on} - C_{supplied}$ at 350 CMH sometimes did not exceed zero concentration, (Figure 3) yielding the calculated CE over 1 (100%). This is assumed that exhaust flow rate of the range hood was adequate or higher than the kitchen needed to remove the particles. (Generated by cooking and supplied through the diffuser). One of the experiment cases with 350 CMH was excluded in Figure 4 for this reason, to get conservative results.

CE generally improved with the range hood exhaust rate, especially for the small and large particles, owing to the CE of upward convex shape as the particle size increases at the 250 CMH, while CE decreases when the particle size increases at the 350 CMH. This implies that for both exhaust rates, larger particles are harder to remove through range hoods, but the efficiency differs by the exhaust rates for the smaller particles. In this study, it assumes that smaller particles are harder to remove with the lower exhaust rates and the efficiency improves

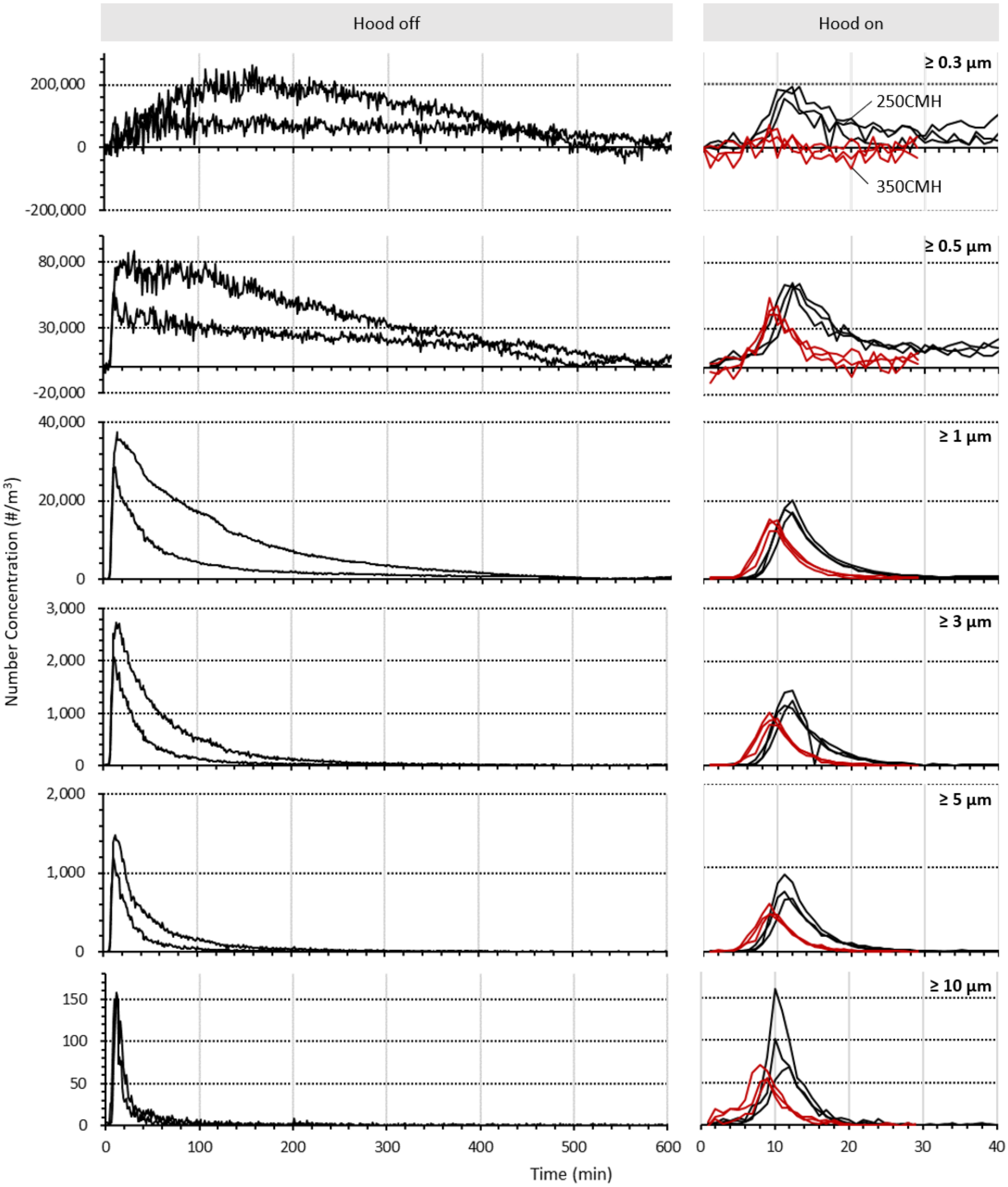

Figure 3: Measured particulate concentration of the kitchen subtracted from the estimated background concentration. Estimations were based on the approximated penetration coefficient and deposition rate for the ‘hood off’ case, and the removal efficiency of the supply fan and deposition for the ‘hood on’ case. Experiments were repeated twice for the ‘hood off’ case and thrice each for the ‘hood on’ cases at exhaust rates of 250 m^3/h and 350 m^3/h, respectively. All experimental cases in this study are shown in the graphs.

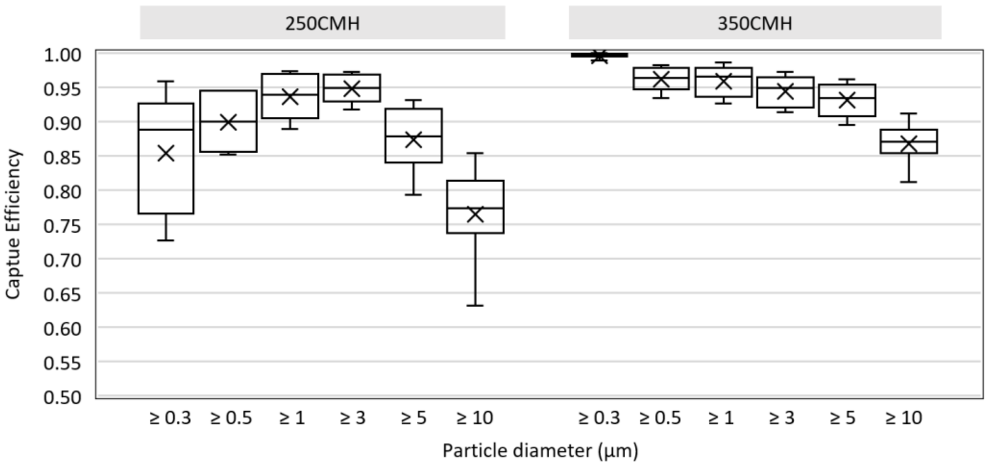

Figure 4: Capture efficiency of particles generated from bacon-cooking for the chimney type kitchen range hood at an exhaust flow rate of 250 m³/h and 350 m³/h, respectively.

sharply as the exhaust rates increases. Similar CE at the particle size between 1 μm to 5 μm was observed. (0.89 - 0.97 at 250 CMH and 0.91 – 0.99 at 350 CMH) At this particle size range, there is no substantial difference in the CE.

The positive correlation between exhaust flow rates and CEs can also be observed in other studies. Although the CE was calculated by concentration of CO_2 in the study of Singer et al. (2012), the CE also increased with increasing exhaust flow rate. Lunden et al. (2015) also found that the CE increased with exhaust flow rate for a particle size range of 6–15 μm when using the front burner (as was the case in our study) for all hood types, fan speed settings, and particle diameters. However, the CEs observed by Singer et al. were much lower than ours, being 4–39%, even though the exhaust flow rate was 51–138 l/s. (183.6–496 m^3/h) This indicates that the experimental setting, location of OPCs, and calculation method can lead to different CE results.

There are some limitations in this study: (1) measurement of the ultrafine particles (UFPs) was not conducted. Cooking activity generates substantial amount of UFPs and other similar studies reported the efficiency of the range hood regarding UFPs. For example, Rim et al. (2012) showed reduction effectiveness of UFPs increased with the particle diameter up to 14 nm. (2) The complete mixing of the kitchen is not guaranteed. Some study utilized mixing fan to minimize the impact of short circuiting and to achieve generally well-mixed condition around the room. (Lunden et al., 2015) Because of the intensive generation (bacon-frying) and removal (kitchen hood exhaust) of particles in a specifically small area, a well-mixed particle concentration within the kitchen volume is difficult to achieve. Hence, the CE in equation 6 in the section 2.5 refers to the value at the measurement point, not the representative average value. However, considering the small size of the kitchen in this study, the calculated CE is expected to be similar except right below the range hood.

4 CONCLUSIONS

This study compares the coarse particle removal performance of range hoods at exhaust flow rates of 250 m^3/h and 350 m^3/h, respectively, based on CE. The experiments were conducted in a test testbed designed as a kitchen, but which was not completely air-tight and used an unfiltered air supply, as is common in most households. To determine the CE under these conditions, the unfiltered particle concentration was estimated and subtracted from the measured concentration to establish the contribution of cooking only to the particle concentration. The CEs of most of the evaluated particle sizes at an exhaust rate of 250 m^3/h were 0.63–0.93, while those at 350 m^3/h were 0.81–0.99, indicating that CEs were greater at

350 m^3/h than at 250 m^3/h with slight differences, except for the middle size ranged particles that showed similar CEs at both exhaust rates. The CEs of the smaller particles (≤ 3 μm) was harder to remove through the exhaust range hood when it is operating at 250 CMH, so higher exhaust rate is needed to improve the CE since most of the particles generated from the cooking activities are smaller particles.

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