Experimental Study of Exposure to Cooking Emitted Particles under Single Zone and Two-zone Environments

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Keywords: cooking generated particles; kitchen hood; two-zone transport; indoor air quality, exposure, ultrafine particles.

Abstract

Cooking is a major indoor pollutant source. It is important to know the exposure not only inside but also outside the kitchen. However, the spatial distribution of particle concentration in two indoor zones has not been studied extensively. Therefore, this study investigated particle transport between two zones for a water boiling process under four kitchen hood operation scenarios. Particles were counted using a condensation particle counter; since most of the particles were less than 100 nm in diameter, the study may be considered a study of ultrafine particles. If the range hood operates during the cooking period, or both during and after the cooking period, exposures can be substantially reduced. For the single zone scenario (connecting door closed), operation of the hood during the cooking period reduces exposure by 87 to 92%, compared to the no-hood operation. When the door between the two zones is opened and the hood is not operated, the exposure in non-kitchen zone ranged from 30% to 54% of that near the stove. Strong exhaust airflow from the kitchen hood interacted with the ventilation airflow, generating complex airflow which resulted in varying concentrations at different points in the kitchen zone. Under the scenario with the range hood off both during and after cooking, comparing at point nearest the stove, the exposure at the other points ranges from 65 to 90% while under the range hood on both during and after cooking scenario, the exposure ranges from 30 to 90%.

Keywords: Cooking emitted particles, Two-zone transport, Kitchen hood, Particle transport, Exposure

1. Introduction

People stay indoors most of their time [1]. In a non-smoking household, cooking is often the major source of pollutants, including aerosols [2-4] and gaseous pollutants [5,6]. A recent article provides an excellent review on aerosol size characteristics and chemical compositions generated by different cooking styles [7]. The authors also commented that Chinese cooking style generates much higher PAHs than western style cooking.

Once emitted, aerosols disperse inside kitchens. In most literature studies a well-mixed condition was assumed or only a single location measurement was taken [8-11]. Other studies only focused on the exposure measurement close to the source [12-14]. This may characterize the exposure of the cook, but not necessarily that of other members of the household. Bhangar et al. [15] measured exposure for 7 houses. They concluded that for indoor-generated particle sources, near-source exposure can be significantly higher.

Some studies have considered concentrations in different zones due to cooking. Rim et al. [11] measured cooking emitted particle concentration in a full-size manufactured house. Concentration levels in the master bedroom and kitchen were measured. However, no inter-zone correlation was proposed. Lai and Chen [16] simulated cooking activity in a flat containing a kitchen and a non-kitchen area. They found that well-mixed concentrations may not be achieved inside kitchens due to the strong local buoyancy effect. Both temperature and concentration profiles showed a large variation in the kitchen and non-kitchen area. Furthermore, the spatial concentration variation in a kitchen was also studied by Lai and Ho [17]. They conducted an experiment in a real residential kitchen and a numerical simulation under a low air exchange condition. Results showed that the concentration could be 3 times higher at

a location of 0.3 m from cooking stove when compared with that sampled at the location of 2.8 m from the cooking stove. These two studies indicated that spatial variation could be found within a single zone (i.e. only kitchen was considered) as well as two-zone micro-environments. Other studies focused on spatial variation of particulate matter (PM) in domestic apartments [8,18-21]. They reported that concentration variation could be found between a kitchen and living room, although some studies showed a negligible difference between zones. However, these studies focused on fine and coarse particles. Ultrafine particles (< 100 nm) are now of great interest due to their production by cooking with both electric and gas stoves [22]. Wan et al. [10] conducted a field measurement focusing on ultrafine particles in 12 residential homes. The cooking activities were controlled by those residents. The authors measured both the number and mass concentrations in living rooms and kitchens. However, they only reported the 12-site average values without any details of cooking conditions. The status of operation of range hood, cooking style, and cooking duration were not specified and reported. Since those cooking conditions could influence the transport of particles, without this information, it is impossible to calculate exposure at different locations inside a home.

Adverse health effects, such as respiratory symptoms and lung cancer, have been widely reported to be positively associated with exposure to cooking [23-25]. Recent study in Taiwanese families showed that poor ventilation led to $PM_{3.2}$ $160 \mu g/m^3$ [6]. Thus it is essential to reduce exposure to the cooking-generated pollutants. People commonly use domestic kitchen range hoods to maintain better indoor air quality in residential kitchen. Some studies have tested different parameters regarding kitchen hoods, such as exhaust flow rate, distance between stove and hood, front and back burners, etc. They showed that these variables could influence human exposure

to cooking pollutants or capture efficiency of the hood [11,26]. In a recent article the authors measured capture efficiency for aerosols by a 6-bins optical particle counter and a condensation particle counter. They found that capture efficiency for gaseous pollutants is different from aerosols, which further complicates the issue [27]. Previous studies and conclusions concerning gaseous pollutants may not be applicable to or validated for aerosols.

There are knowledge gaps on understanding and quantifying exposure inside and outside the cooking zones. Thus the objectives of this study lie in a few areas; (1) studying homogeneity of cooking-generated particles concentration within a single-zone (cooking zone); (2) quantifying the particles transport to the non-cooking zone; (3) influencing of hood operation on exposure.

2. Study Design and Procedures

2.1 Study design and methodology

An environmental controlled chamber with dimensions 4.6 m (L) $\times$ 2.25 m (W) $\times$ 2.3 m (H) was used as a mock-up for performing our cooking activities. The chamber is divided into two equal volume zones, named as kitchen zone and non-kitchen zone, each 2.3 m in length. A door of dimension 0.9 m (W) $\times$ 2 m (H) is located at the partition such that closing this door can separate the two zones. The chamber is made of stainless steel with very smooth surfaces. A well-mixed (WM) ventilation system was operated throughout the study, where the air exchange rate was set to be 6 h⁻¹. Before starting the experiments, leakage test was conducted. Differential pressure of 20 Pa was applied and measured by a manometer when CO₂ was simultaneously injected to the room. Analysis of the CO₂ decay plot yielded the leakage rate, which is

approximately 0.1 ACH under the specified pressure difference of 20 Pa and can be ignored compared to the supply air rate.

A new, non-commercial grade domestic kitchen range hood with the dimension of 0.7 m (L) $\times$ 0.525 m (W) $\times$ 0.135 m (H) was selected. The range hood was installed at a height of 1.58 m inside the kitchen zone of the chamber, 0.75 m above the cooking stove. The height is within the range of distance of 60 to 90 cm above the cooking stove recommended by the manufacturer. Figure 1 shows the three-dimensional installation plan of the domestic kitchen hood. An exhaust air duct was connected to the space outside the environmental chamber. The air was filtered by a HEPA filter before it discharged to the laboratory. As the real exhaust flow rate would be affected by the length of exhaust air duct and the additional HEPA filter, the flow rate of operation of the single exhaust fan was measured after the complete installation of the kitchen hood. The velocities at 9 points at the outlet of exhaust air duct were measured by a hand-held hot-wire anemometer (9555, TSI; accuracy of $\pm 3\%$). There are three exhaust airflow settings; low, medium and high. In this study, the exhaust flow rate is not the focus and hence, only one exhaust flow rate (the lowest setting) was set throughout experiments. As the chamber is not large, the lowest exhaust flow rate was expected to provide sufficient performance on exposure reduction. It is calculated using Equation (1) and found to be 483.6 m³/h.

$$Q = \bar{V}A \quad (1)$$

where Q is the exhaust flow rate, $\bar{V}$ and A are the 9-point-averaged velocity and the cross-section area of the exhaust air duct respectively. The equivalent ACH of the hood is 41 h⁻¹. It can be anticipated that this high airflow would interfere with ventilated airflow when operated. Results support this observation.

Figure 1: Three-dimensional layout of the setup and the installation of domestic kitchen hood in the kitchen zone.

To study dispersion inside a single zone and transport between two zones, two types of door scenarios were conducted: door closed or opened (Figure 2). For the experimental set focusing on dispersion in a room (single zone), the door connecting the two zones was closed. Thus all points except sampling point F would not be measured. For the experimental set focusing on particle inter-transport study (two-zone), the door was opened, and all the sampling points were measured. It should also be noted that only water boiling was used for this study. Location A is very close to the stove, if oil were used, it would anticipated that very high concentration, sticky particles were sampled and they may affect the optics of the CPC.

Figure 2: Plan of the testing chamber and the location of sampling points.

The influence of hood performance on cooking-emitted particle concentration was investigated by 4 hood operation scenarios. The kitchen hood was operated for 4 scenarios under each experimental condition: (i) hood turned off (off-off); (ii) hood off during cooking, on after cooking (off-on); (iii) hood on during cooking, then off (on-off) and (iv) hood always on (on-on).

The concentrations at a total of 6 sampling points were measured. Five of them were located in the kitchen zone, while one sampling point was located in the non-kitchen zone. The detailed locations of the sampling points are listed in Table 1. All sampling points were located at a height of 1.55 m, representing the breathing zone of people.

The selection of locations needed elaboration. Location A mimics the location of a cook. It was chosen because it represents the possible exposure of a cook and likely the practical maximum exposure inside the cooking zone. Location B is chosen to represent a person far away from the stove. Location C is at the center point and the result can be taken as an average exposure. Location D represents a position near the

door connecting to the non-cooking zone. It was chosen in order to understand how particles transport to the non-cooking zone. E is at the location under the supply air. It mimics the exposure for a person standing near the mechanical supply diffuser with clean air delivered. F is the location in the non-cooking zone. It mimics exposure of an occupant staying in the zone during the entire cooking period. Overall speaking the selections of these locations supporting the objectives of the study.

Sampling point	x-direction (m)	y-direction (m)	Distance to the stove (m)
A	3.20	0.73	1.41
B	3.45	1.69	1.78
C	3.45	1.13	1.30
D	2.88	1.13	1.34
E	4.03	1.13	1.42
F	1.15	1.13	2.49

Table 1: Details of the sampling locations.

2.2 Experimental procedures

One liter of water was boiled at the peak power level of gas stove for 15 minutes although the water came to a boil in about 8 minutes. An additional 30 minutes was recorded as a decay period. Prior to starting the cooking, 10 minutes of background concentration and temperature were recorded. This period was used to ensure that the current measurement was not affected by the preceding one. The particle number concentration was measured by a Condensation Particle Counter (CPC) (TSI, 3775; accuracy of $\pm 20\%$). The 50% cut off size is 4 nm and the maximum detectable size is 3 μm . Before conducting the experiments, a size-resolved measurement was made

by a SMPS (TSI, 3080 with DMA 3081). It was confirmed that the droplet size generated was less than 100 nm.

The temperatures inside the kitchen zone were monitored by K-type thermocouples controlled by the user-defined LabVIEW environment. The temperature of 22 ± 0.5 °C was considered to be ready for starting a new experimental run. It is anticipated that the emission from cooking is a stochastic process; repeated experimental runs can provide better statistical interpretation for analysis. The experiments were repeated 3 times under the identical conditions.

3. Preliminary Experiments

Since the cooking emission was anticipated to be varied, simultaneous measurement at all sampling points was preferred. Sampling one location at a time and repeating for different points may not accurately show the point-to-point exposure relationship. Therefore, it is necessary to use two instruments recording at two points in the same experimental run. However, due to limitation of instrument availability, two different models of particle counters were used in this study. Concentration at point A was measured in each data set by a Condensation Particle Counter (CPC) (TSI, 3775, accuracy of ± 20 %), while the concentration at one of the other sampling points (B to F) was simultaneously measured by P-Trak (TSI, 8225, assumed accuracy the same as the CPC; ± 20 %). The performance of the two instruments is different, and hence the relative bias between them was calculated before spatial measurements began.

3.1 Testing procedure of relative bias between CPC and P-Trak

It should be noted that the measurable size range of the P-Trak was 20 nm to 1 μm , while that of the CPC was 4 nm to 3 μm . The measurement from these two instruments cannot be compared directly as the emission profile from cooking has been shown to consist of significant amounts of particles between 4 and 20 nm (Wallace et al., 2008). A separate experimental set was conducted to establish a correlation between the P-Trak and the CPC in-situ. This approach could show a more realistic comparison among different sampling points.

The sampling points of the CPC and the P-Trak were put at a particular location (any one of points B to F). Both instruments were allowed to take measurements for the whole experimental period (15 min of cooking and 30 min of decay). The exposures (concentration $\times$ time) measured by the CPC and the P-Trak were found and the relative bias associated with each spatial position i (B_i) was then calculated using the following equation:

$$B_i = \frac{E_{i,C,CO}}{E_{i,PT,CO}} \quad (2)$$

where,

$$E_{i,C,CO} = \sum C_{i,C,CO} - C_{BG} \quad (3a)$$

$$E_{i,PT,CO} = \sum (C_{i,PT,CO} - C_{BG}) \quad (3b)$$

$E_{i,C,CO}$ and $E_{i,PT,CO}$ are the exposures attributable to the indoor source measured by the CPC and the P-Trak at position i respectively. $C_{i,C,CO}$ and $C_{i,PT,CO}$ are the concentrations measured by the CPC and the P-Trak at position i respectively. C_{BG} is

the background concentration of each experimental run. The summation is over time for 45 minutes. B_i was calculated by at least three repeated experiments.

After obtaining the B_i for each location, they were used to calculate the correlated exposure for all locations.

4. Results and Discussion

4.1 Typical concentration profile under four hood operational conditions

Figure 3 shows the typical background subtracted concentration profiles under four hood operational conditions in the single zone environment. The concentration measurement at location B was chosen to be reported here. There are two salient differences among the concentration profiles under four conditions: peak concentration and decay rate after cooking.

Without any hood extraction, the peak concentration of the off-off condition was close to that of the off-on condition, and the peak concentration of the on-off condition was close to that of the on-on condition, but the latter was 7 times lower (Figure 3). The large difference in concentration indicates the hood operation during cooking efficiently extracted the cooking-related pollutants.

Figure 3: Example concentration profiles under four hood operational conditions in single zone environment (measured at point B): (a) off-off; (b) off-on; (c) on-off; and (d) on-on condition.

The different characteristics of concentration profiles shown in Fig 3 confirm that the different hood operation patterns significantly influence the ultimate exposure. Comparing to the off-off scenario, the exposure at point B for off-on, on-off and on-on scenarios are 82%, 12.9% and 8% respectively. Exposure reductions at other locations will be addressed later (*c.f.* Figure 6).

Another salient difference in concentration profiles was the decay rate. The decay rate is the sum of the air exchange rate and the deposition rate. When the hood was operated during the decay period, the decay rate was faster than without hood operation. The decay rates under off-off and on-off conditions were 6.32 h^{-1} and 7.69

h^{-1} respectively, about 2.5 times lower than those under off-on and on-on conditions (16.68 h^{-1} and 19.37 h^{-1} , respectively). The high exhaust flow rate of the hood greatly increased the air change rate of the chamber, which could help to flush the kitchen zone and return to background concentration rapidly.

In the following sections, three factors affecting concentration were identified and further explored: effect of opening of door on exposure in kitchen zone; effect of physical location and effect of hood operational condition.

4.2 Effect of door opening on exposure in the kitchen zone

In some metropolitan cities such as Hong Kong, the kitchens are generally very small. The cook tries to reduce the temperature and the fumes inside the kitchen and the common practice is to open a window. Nonetheless during winter time, it is more common to open a kitchen door when meal is undergone preparation. Thus, for the present work it is useful to know how opening the partition door affects the exposure in the kitchen zone.

We first conducted experiments without any hood operation for single and two zones and compared the results (Figure 4). The measurement was taken at location B. Under two-zone scenarios, the concentration was 50% of that for the single zone. The results imply that the involvement of the non-kitchen zone reduced exposure in kitchen zone, which may be mainly due to the increase of volume.

Figure 4: Concentration profiles at point B of single zone and two-zone environments under off-off condition.

To investigate the effect of door opening on exposure reduction, a ratio $E_{i,2/1}$ was defined to quantify the influence of door opening for different locations i in the cooking zone by calculating the averaged exposure ratio for the two-zone to single-zone condition. The equation is shown as follows:

$$E_{i,2/1} = \frac{\sum(C_{i,p,TZ} - C_{BG})}{\sum(C_{i,p,SZ} - C_{BG})} \times 100\% \quad (4)$$

where $C_{i,p}$ is the concentration at sampling point i under hood operational conditions p . TZ and SZ represent two-zone and single zone measurement, respectively.

Figure 5 shows the $E_{2/1}$ ratios under different hood operational conditions. Because of the volume increase, all sampling points in kitchen zone obtained a lower exposure

level in two-zone environment (i.e. less than 100%) for all operational conditions than in the single zone environment as expected. It is interesting to note that the reduction levels were different among different locations within this small zone.

Figure 5: $E_{2/I}$ ratio under four hood operational conditions at points A to E. Error bars represent one standard error.

Relatively high ratios are observed for point A under all 4 hood operations. When the hood was not operated (off-off condition), or only operated during non-cooking period (off-on condition), the exposure was found to be only slightly lower than that in the single zone environment, while hood operation during cooking (on-off and on-on conditions) showed an exposure reduced to just only 50%. The plausible rationale is that among all sampling points, point A is the closest location from the stove. It could be anticipated that external environmental parameters were least affected at this point compared with other remoter locations. The highest ratios (compared to other

spatial points) are observed regardless of the operation of the hood. Two conclusions can be inferred; (1) the exposure for the cook is very difficult to reduce significantly using the range hood and (2) the pollutant is not well-mixed. The latter issue will be discussed further below.

Another point showing high ratios is point D. At location D, under off-off and off-on conditions, the high ratios can be plausibly attributed to its location close to the exhaust air grille and the door. When the hood is not operated (off-off), the mechanically-ventilated exhaust of each room (both kitchen and non-kitchen zones) dominates the airflow inside the room. More particles would be transported towards this point by mechanical ventilation. When the hood was not operated during the cooking period, high concentrations occurred in the kitchen zone. Due to the diffusion process, the particles were transported to the non-kitchen zone. Since location D was near the connecting door, when particles were transported to the non-kitchen zone, high concentrations would result. That explained why under off-on condition lower concentration, the ratio at D is high.

4.3 Exposure ratios at different physical locations

Figure 6 shows the concentration profiles in the kitchen zone under off-off condition. Apart from point E, other sampling points show a comparable peak concentration. This could show that the chamber is nearly well-mixed. This may be due to the small volume of the single zone in our experimental chamber; the particles generated by cooking were easily transported to other locations by means of strong buoyancy, mechanical convection and diffusion. Point E was located near the supply grille where filtered air was supplied. This leads to lower concentration peak at this point.

Figure 6: Concentration profiles in single zone environment under off-off condition.

It is also interesting to compare the exposure to the point nearest to the stove (Point A) which is normally where the cook stands. All the concentrations at points B to F were normalized to that at point A under different hood operational conditions. The exposure ratio is defined as follows:

$$ER_{A,p} = \frac{\sum(C_{i,p} - C_{BG})}{\sum(C_{A,p} - C_{BG})} \times 100\% \quad (5)$$

where $ER_{A,p}$ is the exposure ratio relative to point A under hood operational condition p , $C_{A,p}$ is the concentration at sampling point A under at same operational condition p .

Figure 7 (a) compares exposure at all sampling points to Point A for the single-zone case. If conditions are homogeneous, $ER_{A,p}$ should equal 100% at all points. However, this was not achieved at any point for any hood operating condition. Under off-off scenario, the range of ER_A is 65 to 90% while under on-on scenario, ER_A ranges from 30 to 90%. This confirms that operating the hood created an inhomogeneous environment. Point B, the farthest point from the stove, shows a comparatively low exposure ratio (45.6 % and 29.9 % for on-off and on-on conditions respectively), suggesting that, relative to the cook, operating the hood reduced the concentration most at the farthest location.

Figure 7 (b) shows the results under the two-zone environment. Compared with Figure 7 (a), very different results were observed. All sampling points in the kitchen zone showed a lower exposure ratio than in the single-zone case but with a larger variation among locations. The increased volume of the chamber under the two-zone condition reduces exposures in both zones as shown in Fig. 4.

(a)

(b)

Figure 7: Exposure ratio relative to point A under four hood operational conditions. (a) Single zone; (b) Two-zone. Error bars represent one standard error.

Under off-off and off-on conditions, a relatively high ratio was found at point D. This observation can be explained by ventilated airflow and location of the door. Each zone has an individual ventilation system. Generated particles were transported towards this point by mechanical ventilation. When the door is opened, particles would be transported to the lower concentration non-kitchen zone by diffusion process. Thus, a higher ER_A at point D results. In light of this argument, point F also obtained a surprisingly high exposure ratio, where ratios of 54.7 % and 30.6 % were found under off-off and off-on conditions respectively. Interestingly these magnitudes were higher than those at point E. This showed that without the hood operation during active cooking period, the exposure at the non-kitchen zone would be also considerable, and definitely not negligible. However, when the hood was operated during cooking, the exposure ratios of all points dropped to less than 15.5 %. This indicated that the operation of hood could efficiently control the particles transport in

two-zone condition. This has important implications for practical scenarios; to reduce exposure in non-kitchen zones, active exhaust should be utilized and/or the door should be closed between the kitchen and the other zones.

It can be seen that ER_A is very low at positions B, C, D and E for on-off and on-on scenarios. This can be explained by the airflow. Previous simulation results of an exhaust hood installed in a single zone showed that airflow is complex [28,29]. Thus it would be anticipated that in the two-zone environment, the airflow pattern is more complex by the combination of the individual mechanical ventilation systems in each zone and the inter-zonal airflow which would be affected by the strong exhaust airflow induced during the hood operation. Operation of the hood exhaust pulls “clean” air from the non-kitchen zone to the kitchen zone. This may further dilute the particle concentration inside the kitchen zone.

4.4 Effect of hood operational condition

The effect of different hood operational conditions was also studied. Here a new parameter, defined as an exposure ratio relative to location A when the fan is not operated at all (the off-off condition), is proposed.

$$ER_{i,A,OO} = \frac{\sum(C_{i,p} - C_{BG})}{\sum(C_{A,OO} - C_{BG})} \times 100\% \quad (6)$$

where $ER_{i,A,OO}$ is the exposure ratio at any point i of hood operation p relative to the measurement under off-off condition at point A, $C_{A,OO}$ is the concentration at the sampling point A under the off-off scenario.

Figure 8 shows the averaged exposure ratios of various hood operational conditions relative to the off-off scenario at different points.

Figure 8: Exposure ratio with off-off scenario at different points. (a) Single zone; (b) Two-zone. Error bar represents one standard error.

For the single-zone environment (Fig 8a), the exposure ratios under a particular hood operation were varied moderately under off-on condition. As expected, the off-on condition produces the highest ratios (65-83%) while the on-on and on-off conditions give much lower results, ranging from 9-38%. The results indicated that operating the hood during active cooking (i.e. on-on and on-off conditions) can significantly reduce pollutant exposure while the effectiveness of the hood is minimal if employed only after the cooking period (i.e., off-on condition). The exhaust airflow rate measured was 483.6 m³/h. The equivalent ACH is 40.6 h⁻¹. It is approximately equal to 6.7 times of the mechanical airflow. Thus, it is anticipated that operation of such hood would dominant the pollutant removal.

Nevertheless the ratios varied substantially at different locations. From Figure 8 (a), under off-on condition, the exposure ratios at most of the sampling points were comparable (about 70%) but point E obtained a relatively higher exposure ratio (83.5 %). In fact the exposure ratio at point E was also found to be higher than those at other points regardless of the hood operational conditions. It might be attributed to the location of point E right under the supply air grille. The high velocity jet of supply air reduced the effect of the hood operation and hence, exposure could not be reduced as much as those other locations. On the other hand, the exposure ratio at point A (the closest sampling point to the cooking stove) was higher under on-off and on-on conditions compared with points B, C and D. Point A, the closest physical location to the cooking stove, shows the most limited exposure reduction by hood operation.

In the two-zone environment (Fig. 8b), under the off-on condition, the exposure ratios were still high, ranging from 50% to approximately 100%. However, for points B-F, the effect of the fan operating during the cooking process was very strong, reducing exposure by at least 95% in all cases. Point A was also considerably reduced, by

about 80%. This also agrees with the previous results that hood operation controls the particles transport better in two-zone condition (Figure 7).

The results in both single zone and two-zone environments showed that the reduction in exposure by operating the range hood during the non-cooking period was small. On the other hand, when the hood was operated during the cooking period, the exposure was reduced more efficiently at all locations. The exposure reduction obtained was compared with that reported by Rim et al. [9] which was ranged from 31 to 98%.

Finally it should be noted that the current experiments were conducted in a 11 m³ chamber. Although this size is small by Western standards, in many metropolitan cities, particularly in South East Asian countries, kitchen and home sizes are generally small compared to those in Western countries [6]. This would result in higher concentrations in both zones.

Although coagulation was not the focus of the present study, it is important to notice that cooking-generated particles are at high temperature, thermal-induced coagulation should be considered [30] as it affects the particle size evolution which leads to ultimate adverse health effects.

5. Conclusions

The results showed that both the number of zones and the times of operating the range hood significantly influenced exposure. The hood operation during cooking was found to be dominant in reducing exposure at most locations, although the exposure of the cook was not reduced as much. In fact, it is observed that the cook's exposure is difficult to reduce significantly under the current experimental conditions. If the

hood was operated only during the non-cooking period, the reduction would be limited at all points in the room.

Airflow was found to be a significant factor affecting the exposure under different conditions, especially in the two-zone environment. The location of the return air grille at the kitchen zone and the door thus allowed the cooking fume to transport from the kitchen zone to the non-kitchen zone. The exposure in the non-kitchen zone could possibly increase to level comparable with that in kitchen zone when the hood was not operated. Nonetheless the operation of the hood pulled out clean air from the non-kitchen zone to the kitchen zone which further decreased the exposure inside the kitchen. The strong exhaust airflow also interacted with the existing ventilation airflow and complex airflow structure was formed. Results also show that exposure was least affected by door opening or hood operation at positions near the stove and under the supply air grille.

6. ACKNOWLEDGMENTS

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Captions of Table and Figures

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References

- [1] N.E. Klepeis, W.C. Nelson, W.R. Ott, J.P. Robinson, A.M. Tsang, P. Switzer, J.V. Behar, S.C. Hern, W.L. Engelmann, The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants, *J. Expo. Anal. Environ. Epidemiol.* 11 (2001) 231-252.
- [2] C. He, L. Morawska, J. Hitchins, D. Gilbert, Contribution from indoor sources to particle number and mass concentrations in residential houses, *Atmos. Environ.* 38 (2004) 3405-3415.
- [3] D.A. Olson, J.M. Burke, Distributions of PM_{2.5} source strengths for cooking from the research triangle park particulate matter panel study, *Environ. Sci. Technol.* 19 (2006) 1110-1117.
- [4] L.A. Wallace, S.J. Emmerich, C. Howard-Reed, Source strengths of ultrafine and fine particles due to cooking with a gas stove, *Environ. Sci. Technol.* 38 (2004) 2304-2311.
- [5] Md. Aynul Bari, W.B. Kindzierski, A.J. Wheeler, M. Héroux, L.A. Wallace, Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, *Build. Environ.* 90 (2015) 114-124.
- [6] K-P. Yu, K.R. Yang, Y.C. Chen, J.Y. Gong, Y.P. Chen, H-C. Shih, S-C. C Lung, Indoor air pollution from gas cooking in five Taiwanese families, *Build. Environ.* 93 (2015) 258-266.
- [7] K.L. Abdullah, J.M. Delgado-Saborit, R.M. Harrison, Emissions and indoor concentrations of particulate matter and its specific chemical components from cooking: A review, *Atmos. Environ.* 71 (2013) 260-294.

- [8] E. Wigzell, M. Kendall, M.J. Nieuwenhuijsen, The spatial and temporal variation of particulate matter within the home, *J. Expo. Anal. Environ. Epidemiol.* 10 (2000) 307-314.
- [9] S.C. Lee, W.M. Li, L.Y. Chan, Indoor air quality at restaurants with different styles of cooking in metropolitan Hong Kong, *Sci. Total Environ.* 279 (2001) 181-193.
- [10] M.P. Wan, C.L. Wu, G.N. Sze To, T.C. Chan, C.Y.H. Chao, Ultrafine particles, and PM_{2.5} generated from cooking in homes, *Atmos. Environ.* 45 (2011) 6141-6148.
- [11] D. Rim, L.A. Wallace, S. Nabinger, A. Persily, Reduction of exposure to ultrafine particles by kitchen exhaust hoods: The effects of exhaust flow rates, particle size, and burner position, *Sci. Total Environ.* 432 (2012) 350-356.
- [12] G.J. Evans, A. Peers, K. Sabaliauskas, Particle dose estimation from frying in residential settings, *Indoor Air* 18 (2008) 499-510.
- [13] R. Kamens, C.T. Lee, R. Wiener, D. Leith, A study to characterise indoor particles in three non-smoking homes, *Atmos. Environ.* 25 (1991) 939-948.
- [14] N.E. Klepeis, Validity of the uniform mixing assumption: Determining human exposure to environmental tobacco smoke, *Environ. Health Perspect.* 107 (1999) 357-363.
- [15] S. Bhangar, N.A. Mullen, S.V. Hering, N.M. Kreisberg, W.W. Nazaroff, Ultrafine particle concentrations and exposures in seven residences in northern California, *Indoor Air* 21 (2011) 132-144.
- [16] A.C.K. Lai, F.Z. Chen, Modeling of cooking-emitted particle dispersion and deposition in a residential flat: A real room application, *Build. Environ.* 42 (2007) 3253-3260.

- [17] A.C.K. Lai, Y.W. Ho, Spatial concentration variation of cooking-emitted particles in a residential kitchen, *Build. Environ.* 43 (2008) 871-876.
- [18] H.S. Huboyo, S. Tohno, R. Cao, Indoor PM_{2.5} characteristics and CO concentration related to water-based and oil-based cooking emissions using a gas stove, *Aerosol Air Qual. Res.* 11 (2011) 401-411.
- [19] J. Jones, S. Stick, P. Dingle, P. Franklin, Spatial variability of particulates in homes: Implications for infant exposure, *Sci. Total Environ.* 376 (2007) 317-323.
- [20] L. Tian, G. Zhang, Q. Zhang, D.J. Moschandreas, J. Hao, J. Lin, Y. Liu, The impact of kitchen activities on indoor pollutant concentrations, *Indoor Built Environ.* 17 (2008) 377-383.
- [21] J. Gao, C.S. Cao, Q.F. Xiao, B. Xu, X. Zhou, X. Zhang, Determination of dynamic intake fraction of cooking-generated particles in the kitchen, *Build. Environ.* 65 (2013) 146-153.
- [22] L.A. Wallace, F. Wang, C. Howard-Reed, A. Persily, Contribution of gas and electric stoves to residential ultrafine particle concentrations between 2 and 64 nm: Distributions and emission and coagulation rates, *Environ. Sci. Technol.* 42 (2008) 8641-8647.
- [23] J.W. Chen, S.L. Wang, D.P.H. Hsieh, H.H. Yang, H.L. Lee, Carcinogenic potencies of polycyclic aromatic hydrocarbons for back-door neighbors of restaurants with cooking emissions, *Sci. Total Environ.* 417 (2012), 68-75.
- [24] Y.C. Ko, L.S.C. Cheng, C.H. Lee, J.J. Huang, M.S. Huang, E.L. Kao, H.Z. Wang, H.J. Lin, 2000, Chinese food cooking and lung cancer in women nonsmokers, *Am. J. Epidemiol.* 151 (2000) 140-147.

- [25] I.T.S. Yu, Y.L. Chiu, J.S.K. Au, T.W. Wong, J.J. Tang, Dose-response relationship between cooking fumes exposures and lung cancer among Chinese nonsmoking women, *Cancer Res.* 66 (2006), 4961-4967.
- [26] B.C. Singer, W.W. Delp, P.N. Price, M.G. Apte, Performance of installed cooking exhaust devices, *Indoor Air* 22 (2012) 224-234.
- [27] M.M. Lunden, W.W. Delp, B.C. Singer, Capture efficiency of cooking-related fine and ultrafine particles by residential exhaust hoods, *Indoor Air* 25 (2015) 45-58.
- [28] K.W. Yi, Y.I. Kim, G.N. Bae, Effect of air flow rates on concurrent supply and exhaust kitchen ventilation system. *Indoor Built Environ.* 25 (2016) 180-190.
- [29] K.B. Lim, C.H. Lee, A numerical study on the characteristics of flow field, temperature and concentration distribution according to changing the shape of separation plate of kitchen hood system, *Energy Build.* 40 (2008) 175-184.
- [30] A.C.K. Lai, J. Chen, Numerical study of cooking particle coagulation by using an Eulerian Model, *Build. Environ.* 89 (2015) 38-47.