Reduction of exposure to ultrafine particles by kitchen exhaust hoods: The effects of exhaust flow rates, particle size, and burner position

Donghyun Rim
Lance Wallace
Steven Nabinger
Andrew Persily

Indoor Air Quality and Ventilation Group, Energy and Environment Division
Engineering Laboratory, National Institute of Standards and Technology
100 Bureau Drive Gaithersburg, MD 20899

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Abstract

Cooking stoves, both gas and electric, are one of the strongest and most common sources of ultrafine particles (UFP) in homes. UFP have been shown to be associated with adverse health effects such as DNA damage and respiratory and cardiovascular diseases. This study investigates the effectiveness of kitchen exhaust hoods in reducing indoor levels of UFP emitted from a gas stove and oven. Measurements in an unoccupied manufactured house monitored size-resolved UFP (2 nm to 100 nm) concentrations from the gas stove and oven while varying range hood flow rate and burner position. The air change rate in the building was measured continuously based on the decay of a tracer gas (sulfur hexafluoride, SF_6). The results show that range hood flow rate and burner position (front vs. rear) can have strong effects on the reduction of indoor levels of UFP released from the stove and oven, subsequently reducing occupant exposure to UFP. Higher range hood flow rates are generally more effective for UFP reduction, though the reduction varies with particle diameter. The influence of the range hood exhaust is larger for the back burner than for the front burner. The number-weighted particle reductions for range hood flow rates varying between 100 m^3/h and 680 m^3/h range from 31 % to 94 % for the front burner, from 54 % to 98 % for the back burner, and from 39% to 96 % for the oven.

Keywords
Occupant exposure; Ultrafine particles; Gas Stove/oven; Kitchen exhaust hood; Particle reduction effectiveness

1. Introduction

Cooking is one of the most significant sources of ultrafine particles (UFPs, < 100 nm) in homes (Wheeler et al. 2011; Kearney et al., 2011; Wallace and Ott, 2009). Several studies have observed significant increases in UFP concentrations associated with cooking activities (Glytsos 2010; Zhang et al. 2010; Buonanno et al. 2009; Wallace et al. 2008; Stieb et al. 2008; Wallace 2006; He et al. 2004; Abt et al. 2000). Wallace et al. (2008) found indoor UFP concentrations 10 times higher than typical urban outdoor UFP concentrations during gas and electric stovetop cooking, while Zhang et al. (2010) reported increases in UFP exposure up to 550 times background levels during cooking. Gas and electric stoves generate ultrafine particles due to combustion (Dennekamp et al. 2001) and from the heating elements (Schripp et al. 2011;

Schmidt-Ott 1988), respectively. The majority of the particles (> 90 %) emitted from gas/electric stoves have been seen to be less than 10 nm with the peak concentration occurring around 5 nm to 6 nm (Wallace et al. 2008). Kearney et al (2011) found that about two-thirds of the 100 Canadian homes studied had higher contributions to indoor UFP concentrations from indoor sources (mainly cooking) than from the entry of outdoor UFP.

Exposure to UFP can lead to adverse health effects such as oxidative stress-induced DNA damage and respiratory and cardiovascular mortality among susceptible individuals (Brook 2008; Oberdörster et al. 2005; Stölzel et al. 2007). UFP deposition in human lungs has been associated with inflammation and impairment of the cells in the lung (Brown et al. 2002), as well as enhanced translocation of UFP from the respiratory epithelium towards the circulation system and subsequent target organs (Kreyling et al. 2006).

Indoor UFP concentrations from cooking can potentially be reduced through the operation of a kitchen exhaust hood. However, the effectiveness of an exhaust hood can greatly vary with several factors: hood type, exhaust airflow rate, aerodynamic design, and space conditions. Furthermore, some people may not use kitchen exhaust hoods, possibly due to a lack of knowledge as to reason they are installed or concerns about noise. Parrott et al. (2003) found that about one-third of 78 households studied rarely use kitchen exhaust devices when using the stovetop burner and almost half never use them when using the oven. In some cases, range hoods do not exhaust pollutants to the outdoors but simply recirculate the particles indoors, perhaps after passing through a grease or other coarse filter.

With regard to the exhaust flow rates, lower flow rates could lead to elevated indoor air pollution (relative to higher flow rates) whereas oversized exhaust fans can produce additional energy consumption and maintenance costs (Kosonen et al. 2006). Keil et al. (2004) found that most of the 89 kitchen range hoods inspected in 60 restaurants did not meet the flow criteria specified by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the American Conference of Governmental Industrial Hygienists (ACGIH).

Several studies (Singer et al. 2011; Wang et al. 2007; Huang et al. 2004; Svendsen 2002; Chiang et al. 2000), both experimental and simulation, have demonstrated that operation of kitchen range hoods can reduce cooking-related pollutants, i.e. carbon monoxide, nitrogen dioxide, polycyclic aromatic hydrocarbons (PAHs) and fine particles. A recent study by Singer et al. (2010) investigated fifteen kitchen exhaust hoods covering a range in price, design and performance specification. The study found that kitchen exhaust fans can effectively remove cooking-related pollutants noting that the capture efficiency or pollutant removal are a function of fan design, installed configuration, burner position, and fan speed setting.

Most of the previous studies of pollutant removal due to exhaust hoods have almost exclusively been limited to the gas-phase pollutants or fine particles. Few studies to date have explored UFP, including size-resolved UFP, removal by kitchen exhaust hoods in real building environments: Zhang et al. (2010) found that kitchen exhaust fan operation can increase particle decay rate by a factor of two compared with fan off conditions, even though the study considered only re-circulating exhaust fans and did not report the fan flow rate and size-dependent particle removal.

The primary objective of the present study is to evaluate size-resolved UFP removal with a kitchen exhaust hood. UFP reductions are considered for three different parameters: exhaust hood flow rate, particle size, and burner position.

2. Materials and methods

2.1. Study design

Experiments were conducted in a manufactured house used for indoor air quality research consisting of three bedrooms, two baths, kitchen, family room, and dining and living area (Figure 1). The building has a floor area of 140 m^2 and a volume of 340 m^3. During the tests, a gas stovetop burner/oven was operated in the kitchen, while size-resolved particle concentrations were measured in the master bedroom. This location was chosen to represent general occupant exposure to UFP during cooking and to avoid fluctuating and non-uniform concentrations in the kitchen. During the tests, the central forced air fan was continuously running, re-circulating approximately six house volumes of air per hour in the house, with all interior doors and ventilation system registers open.

Figure 1. a) Manufactured house; b) Floor layout of the house

Figure 2 shows the range hoods and the gas stove/oven in the kitchen. Two range hoods (Hood A and Hood B) were tested in this study. Hood A is a single-speed hood with an exhaust flow rate of 100 m^3/h, which was installed during the construction of the manufactured house. Hood B is a higher performance model that has an adjustable (four-speed) flow control and can generate exhaust flow rates between 170 m^3/h and 830 m^3/h. The airflow rates through the two range hoods as installed were measured using an Alnor balometer (Skokie, IL), with an uncertainty of 4 % to 15 %. The measured airflow rate for Hood A (100 m^3/h) was roughly 60 % of the manufacturer's specification (160 m^3/h) while the flow rates measured with Hood B were within 10 % of the manufacturer's specification (170 m^3/h to 900 m^3/h). The exhaust flow rates presented in the rest of this paper are the measured flow rates.

According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard for residential ventilation (ASHRAE 2010), the required minimum airflow rate for intermittent kitchen exhausts is 170 m^3/h with a maximum sound rating of 3 sones as installed. The Home Ventilation Institute (HVI) guidance (HVI 2008) specifies a minimum flow rate of 68 m^3/h per linear foot of cooking appliances width and a recommended flow rate of 170 m^3/h per linear foot of the width against a wall. In addition, the National Manufactured Housing Construction and Safety Standards (HUD 1994) requires installation of a kitchen ventilation system capable of exhausting 170 m^3/h of air to the outdoors.

With regard to the noise level, HVI recommends sound ratings of 0.9 sones at low speed and 3.5 sones at high speed. There is no specified sound rating for the Hood A. According to the specification of Hood B, the sound level is not greater than 1.2 sones for 290 m^3/h and 4.5 sones for 830 m^3/h. The unit of sone represents a measure of perceived loudness that is evaluated using sound pressure measurements in a standard laboratory setting (HVI 2009). Another metric of noise is dB(A), representing relative loudness of sounds in air, which is a more common metric for environmental measurements. However, dB(A) and sone are not interchangeable units due to the different measurement methods. Based on our measurements of dB(A) using a sound level meter (Larson Davis, Model LXT1), the noise level for both fans ranged from 65 dB(A) to 75 dB(A) over the tested fan flow rates (100 m^3/h to 830 m^3/h). The highest value was observed in the kitchen and the lowest in the master bedroom. These measurements are somewhat higher than those in a study by Singer et al. (2010) that reported sound levels of 40 dB(A) to 71 dB(A) for flow rates ranging from 50 m^3/h to 650 m^3/h.

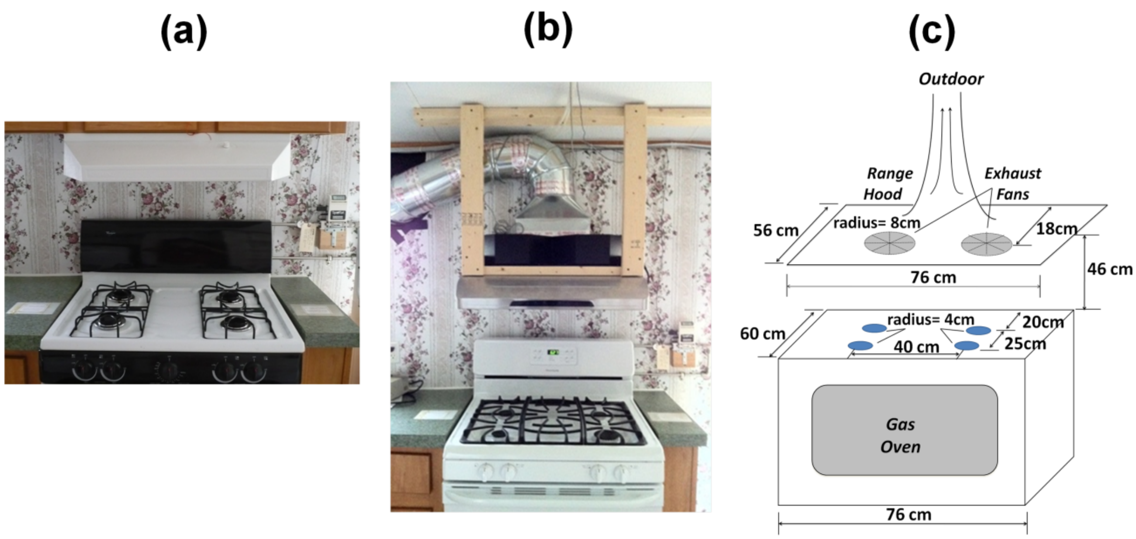

Figure 2. Photographs and schematic of gas stove/oven and range hoods (a) Hood A; (b) Hood B; and (c) Schematic diagram

Considering the information provided above, we tested the two kitchen range hoods at four flow rates: 100 m^3/h (Hood A), 170 m^3/h (Hood B), 370 m^3/h (Hood B), and 680 m^3/h (Hood B). The two range hoods were installed at the same height (46 cm) above the stovetop. Both hoods were tested with grease screens attached. The air captured by the range hood fan was exhausted out of the building without recirculation. Three to six tests were conducted at each test condition: stovetop burners or oven; burner position; and flow rate. The experiments with the stovetop burner and oven were performed without any food cooking, though the stovetop burner tests were done with boiling 0.75 L of water in a pot. For each of the tests, the gas stovetop burner or oven was started simultaneously with the exhaust fan. During the tests, the stovetop burner was turned on for 15 min to 20 min and the gas oven was on for one hour. The average natural gas flow rate was 4.2 L/min for the stovetop burner while it ranged between 0 L/min and 7.0 L/min for the gas oven at a setting of 230 °C. In addition to the effect of the range hood flow rate, the influence of gas burner position on the UFP number concentration in the building was examined by testing the front and back burners with the same range hood flow rate.

2.2. Instrumentation and monitoring

During the experiments, the indoor temperature ranged from 19 °C to 27 °C and relative humidity (RH) ranged from 20 % to 60 %. All of the windows in the house were closed during the tests. Building air change rates were measured with the tracer gas decay method with sulfur hexafluoride (SF_6) injected every 4 hours (ASTM 2000). Using an automated gas chromatograph with electron capture detector (GC-ECD) detection system, the decay of the tracer gas concentration at seven locations within the house was monitored sequentially each minute. The air change rates were calculated as the best fit slope of the natural logarithm of the SF_6 concentration vs. time. The mean and standard deviation of the air change rates for the seven monitoring locations were calculated to check the air mixing inside the house. The relative standard deviations (RSD) for the SF_6 concentrations at the seven monitoring stations were typically smaller than 10 %. The averaged air change rates observed during the tests ranged from 0.15 h^{-1} to 0.54 h^{-1} for the hood-off periods and from 0.46 h^{-1} to 1.65 h^{-1} for the hood-on periods. The measurement errors ranged from 8 % to 15 %, based on combining two independent measurement uncertainties in quadrature. These two uncertainties include the uncertainty due to incomplete air mixing plus precision (4.3 % to 6.5 %) and calibration drift of the instrument (5 %).

The size-resolved UFP concentrations were monitored in the master bedroom using a Scanning Mobility Particle Sizer (SMPS) (Model 3936, TSI, Shoreview, MN), which consists of an electrostatic classifier (Model 3080), nano-differential mobility analyzer (nano-DMA, Model 3085), and water-based condensation particle counter (WCPC, Model 3788). The SMPS system measures particles with aerodynamic diameters ranging from 2 nm to 100 nm using two sheath flow rates of 15 L/min and 6 L/min with 10:1 sheath/aerosol sampling flow ratio. The system monitored particles from 2 nm to 64 nm for the stovetop burner using a sheath flow rate of 15

L/min, and particles from 3 nm to 105 nm for the oven using a sheath flow rate of 6 L/min. An enhanced radiation source (TSI 3077A neutralizer) was used to increase the charging efficiency for the smallest particles. To ensure that particle sampling flow was accurately regulated, sampling flow rates were measured before and after each experiment using a bubble flow rate meter (AP Buck, Inc, Orlando, FL). At least three measurements were taken and the aerosol flow rates were verified to agree within 3 % of the desired flow rate. The UFP monitoring continued throughout the emission period and the subsequent particle decay period. The aerosol sampling rate was set at 2.5 min: 2 min of measurement for 97 particle size categories (upscan) and 30 s for the voltage to return to baseline (downscan). The measurement uncertainty of the UFP number concentration reported by the manufacturer is estimated to be 12 % based on combining the individual uncertainties due to airflow rate, particle charge distribution, voltage adjustment, and particle charge efficiency in quadrature.

2.3. Calculation of particle reduction effectiveness and decay rate

2.3.1. Whole-house particle reduction effectiveness for particle size category *i* (e_i)

Using the measurement data, whole-house UFP reduction effectiveness due to the kitchen exhaust hood was evaluated for the burner and oven tests. For each particle size bin ranging from 2 nm to 100 nm, the particle concentration was integrated over the emission and decay period. The ratio of the integrated particle concentrations between range hood on and off tests was then used to calculate the whole-house particle reduction effectiveness for particles in the *i*th size category (e_i):

$$e_i = 1 - \frac{\sum_{0}^{t_1} C_{Hood\_On}}{\sum_{0}^{t_2} C_{Hood\_Off}} \qquad \text{Equation (1)}$$

where, C_{Hood_On} is the particle number concentration measured with the range hood on, C_{Hood_Off} is the number concentration with the range hood off, t_1 is the time of return to background for the fan on case, and t_2 is the time of return to background for the fan off case.

Equation (1) was applied to particles up to 14 nm for the stovetop burner and 20 nm for the gas oven, as few particles above these sizes were created by the two sources. The uncertainty of the reduction effectiveness for each particle size was estimated as the standard error of the reduction effectiveness obtained from repetitive tests.

2.3.2. Exponential decay rates for different particle size ranges

In addition to estimating the size-resolved particle reduction, the exponential decay rates of the size-resolved UFP were determined for each size category. These exponential decay rates were estimated based on linear regression on the logarithms of the 12 data points (number concentrations) observed for the initial 30 min of the decay period. The negative slope of the regression (in units of inverse hours) is the total decay rate that accounts for air change (ventilation); deposition on surfaces, ductwork, and filters; and coagulation. For each particle size category, the regression was required to have an R^2 value greater than 90 % to be acceptable. Note that particle decay due to air change is the same for all particle sizes while particle deposition and coagulation are size-dependent processes in which smaller particles generally have higher loss rates. Particle coagulation loss is larger with higher UFP concentrations due to increased collision rates; therefore, comparing the exhaust fan on and off cases, coagulation losses are expected to be higher with the fan off than with the fan on.

2.3.3. Number-weighted particle reduction effectiveness (E)

Finally, using the size-resolved particle reduction effectiveness (e_i) and average number concentration for each size, the number-weighted particle reduction effectiveness (E) was calculated for the particle size range from 2 nm to 100 nm:

$$E = \frac{\sum_i (\bar{C}_{i,\text{Hood OFF}} \times e_{i,\text{Hood ON}})}{\sum_i \bar{C}_{i,\text{Hood OFF}}} \qquad \text{Equation (2)}$$

where $\bar{C}_{i,Hood\ OFF}$ is the average particle number concentration for the size category i during a test with no range hood operating; and $e_{i,Hood\ ON}$ is the whole-house particle reduction effectiveness for the size category i that was observed with range hood operating (the value varies with range hood flow rates). This number-weighted particle reduction effectiveness (E), which is specific for each range hood flow rate, represents the integrated UFP reduction for the whole house due to the range hood. Equation (2) was evaluated for the different flow rates and burner positions. This metric provides a general insight into the effectiveness in removing ultrafine particles released from cooking appliances when using kitchen range hood.

3. Results and discussion

3.1. Gas stove: UFP size distribution and effect of range hood

Figures 3a and 3b show the evolution of particle size distributions due to the gas stovetop burner during the decay period (30 min) following the peak concentration. The figures illustrate the temporal change in UFP concentrations observed with the range hood turned off (Figure 3a) and on (Figure 3b). During the decay, the total number concentration decreases with time and the particle size distribution moves toward larger particle size. This trend is caused mainly by coagulation in which particles collide and stick together, resulting in formation of larger particles . The coagulation loss is generally larger at higher concentrations (Nazaroff 2004); therefore the temporal particle loss due to coagulation is larger with the range hood off than with the range hood on. Furthermore, smaller particles have larger coagulation losses due to their higher mobility and higher collision probability than larger particles (Wallace et al. 2008). Figures 3a and 3b indicate that the majority of the particles from the gas stovetop burner are smaller than 10 nm and that the peak number concentration occurs at particle diameters about 5 nm, increasing to larger sizes with time. Comparing the results with the range hood off and on (370 m^3/h) in Figure 3, the peak concentration is reduced by about half when operating the range hood.

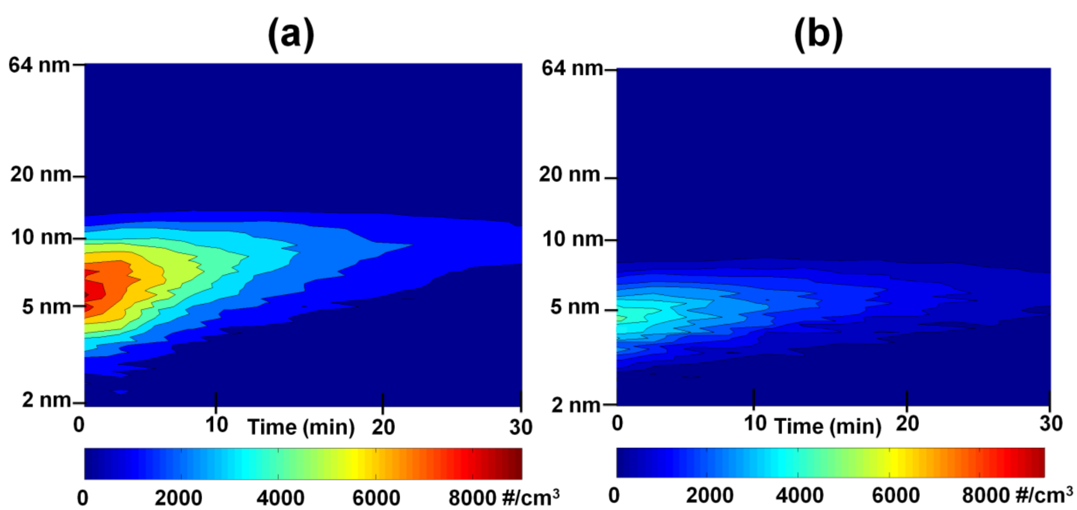

Figure 3 Contour plots of particle size distribution produced by gas stove (front burner) during the decay period following the peak: a) no range hood operating; b) range hood (Hood B) operating with a flow rate of 370 m^3/h. Note that the vertical scale for particle size is logarithmic.

3.2. Gas stove: particle reduction effectiveness (e_i)

Figure 4 illustrates the particle reduction (size-resolved) effectiveness (e_i) for the front burner at three different range hood flow rates (100 m^3/h, 370 m^3/h, and 680 m^3/h). Particle reduction is larger with a higher hood flow rate and for larger particles.

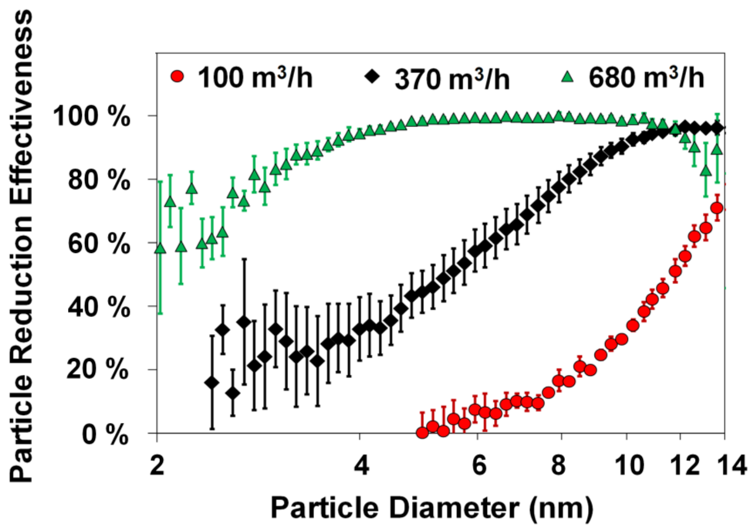

Figure 4 Size-resolved particle reduction effectiveness (e_i) for gas stove (front burner) observed with three flow rates: 100 m^3/h (Hood A), 370 m^3/h (Hood B), and 680 m^3/h (Hood B). Error bars represent standard error from the mean based on repetition tests.

Figures 5a and 5b compare particle reduction (size-resolved) effectiveness (e_i) for the front burner vs. back burner for two range hood flow rates: 100 m^3/h and 370 m^3/h. The higher particle reduction for the back burner demonstrates that the aerodynamics between the particle laden plume and the exhaust hood is different between the back and front burner. The exhaust hood appears to entrain a smaller portion of the plume from the front burner, suggesting that at the same hood flow rate, using the back burner is more effective in reducing particles than the front burner. This observation is similar to that seen by Singer et al. (2010) who observed higher capture efficiencies for back burners of combustion-related contaminants (using CO_2 as a marker).

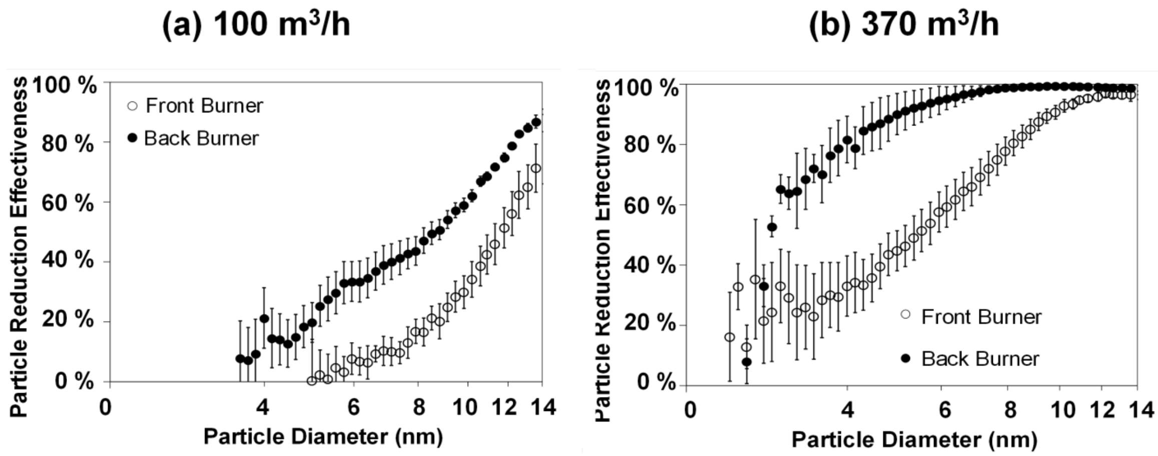

Figure 5 Size-resolved particle reduction effectiveness (e_i) evaluated for front burner vs. back burner: (a) range hood flow rate of 100 m^3/h (Hood A); (b) range hood flow rate of 370 m^3/h (Hood B). Error bars represent standard error from the mean based on repetition tests.

Reduction effectiveness is generally lower for smaller particles. Two factors may contribute to this trend. First, the strong molecular and turbulent diffusion of smaller particles could cause particles to migrate out of the air stream that is flowing towards the exhaust. Secondly, the increased coagulation at high concentration contributes to faster decay rates of the smaller particles during the fan off case. The higher decay rates with the fan off than with the fan on (Figure 6) lead to faster decrease in particle concentrations with the fan off, lowering particle reduction effectiveness (see Equation 1).

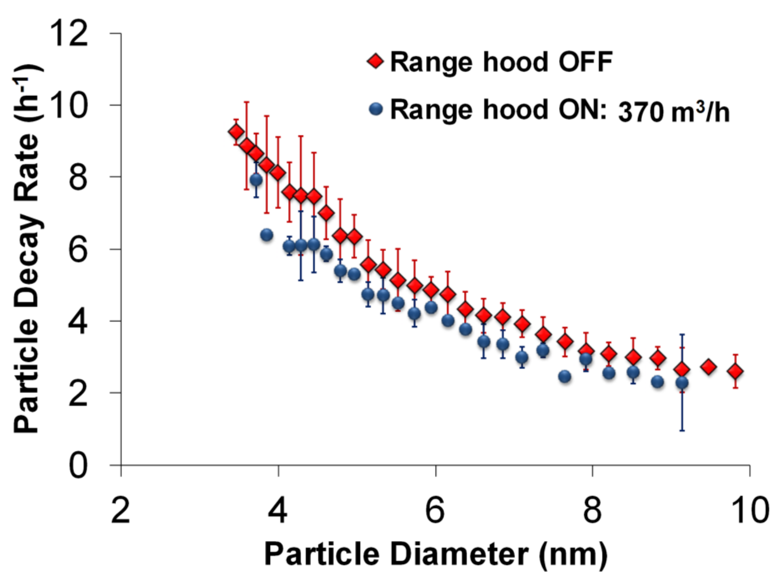

Figure 6 Size-resolved UFP decay rates (due to particle coagulation, deposition, and ventilation) evaluated for the front burner: no range hood operating vs. range hood flow rate of 370 m^3/h (Hood B). Error bars represents standard error from the mean based on repetition tests.

3.3. Gas oven: UFP size distribution and particle reduction effectiveness (*e_i*)

Figures 7a and 7b show the particle size distributions for the gas oven (230 ^oC) observed during the decay period following the total peak concentration. The total number concentrations due to the gas oven are relatively low (about 30 % to 40 %) compared to those from stovetop burners. In the case of the gas oven, the peak concentration occurs around 12 nm, which is different from the results of the study by Wallace (2006) that reported modes at higher diameters of about 45 nm. This discrepancy may be due to the fact that the present study did not include any food-associated combustion whereas Wallace (2006) included cooking (broiling fish and baking potatoes). While the present study was intended to measure the ultrafine particles due to gas combustion only, food types and cooking styles associated with the oven (broil vs. bake) can release different amounts of particles of different sizes, and therefore transform particle size distributions. In addition, although the data are not reported here, we observed that the number concentration due to the gas oven was generally increased at higher oven temperatures.

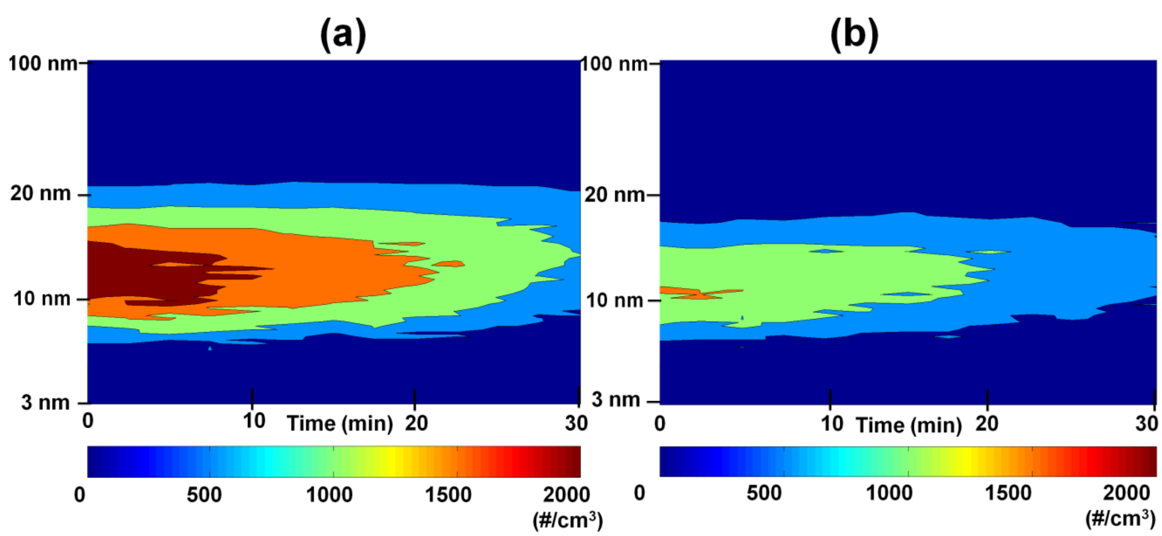

Figure 7. Contour plots of particle size distribution with gas oven: a) no range hood operating; b) range hood operating with a flow rate of 370 m^3/h (Hood B). Note that the vertical scale for particle size is logarithmic.

Comparison of Figures 7a and 7b shows that using a range hood is effective in removing particles from the gas oven. At a flow rate of 370 m^3/h, the peak concentration is reduced by about 30 %.

Figure 8 shows the detailed size-resolved particle reduction effectiveness (e_i) for gas oven at two range hood flow rates: 370 m^3/h and 680 m^3/h. The figure indicates that the UFP reduction is a function of the range hood flow rate and particle size: at 370 m^3/h, the reduction increases with particle size, while at 680 m^3/h the reduction is fairly uniform (above 90 %) over the entire particle size range (4 nm to 20 nm).

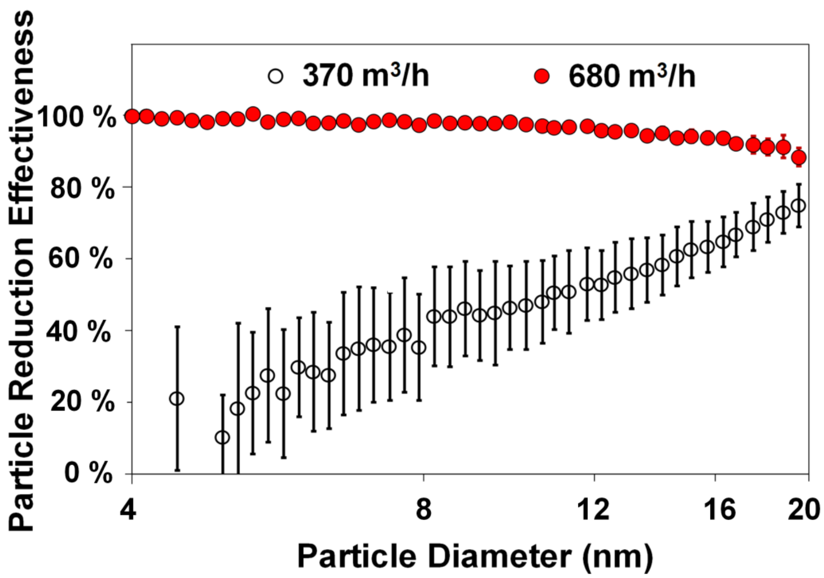

Figure 8 Size-resolved particle reduction effectiveness (e_i) for gas oven observed with two flow rates: 370 m^3/h and 680 m^3/h. Error bars represent standard error from the mean.

3.4. Number-weighted particle reduction effectiveness (*E*) for gas stove and oven

Table 1 summarizes the number-weighted particle reduction (*E*) due to the kitchen range hood. In general, the kitchen range hood is effective in reducing the overall UFP released during cooking with stovetop burners and oven. Higher range hood flow rates are more effective for UFP reduction, and the range hood exhaust is more effective for the back burner than for the front burner.

Table 1. Summary of the average whole-house number-weighted UFP reduction (*E*)

Range Hood Flow Rate (m^3/h)	Front Burner		Back Burner		Gas Oven	
	# of tests	E (SD) (%)	# of tests	E (SD) (%)	# of tests	E (SD) (%)
100 (Hood A)	4	31 (6)	3	54 (9)	-	-
170 (Hood B)	-	-	-	-	4	39 (14)
370 (Hood B)	5	58 (7)	3	88 (16)	4	68 (11)
680 (Hood B)	6	94 (5)	4	98 (5)	4	96 (2)

3.5. Study limitations and implications

It should be noted that the present study considered only two kitchen range hoods in a single test house. Variations in the range hood type, installation configuration, house geometry, and operating conditions could alter UFP transport characteristics and influence the range hood effectiveness. This study did not include cooking food, although it did include boiling water. However, the findings with respect to size-resolved effectiveness of the kitchen range hood are not expected to be affected by the different size distributions associated with cooking food.

The whole-house particle reduction effectiveness observed with the operation of a kitchen range hood is different from the capture efficiency of the range hood (ratio of upstream to downstream concentration). The whole-house effectiveness is affected by house characteristics, particle decay rate, UFP deposition on the indoor and duct surfaces when the central fan is operating as well other factors that do not affect capture efficiency. On the other hand, the capture efficiency can give a direct, quantitative measure of exhaust hood performance, even though it may not represent actual exposure to UFP due to the factors discussed above. In addition, there is no standard procedure to estimate capture efficiency of ultrafine particles in laboratory and field settings. Further studies with additional measurements of the capture efficiency should be performed with careful selection of range hood flow rates and monitoring locations upstream and downstream of the exhaust fan.

While the present study shows that higher kitchen exhaust flow rates are more effective for UFP reduction, the higher flow rate can be significant in terms of the impacts on heating and cooling loads, especially in severe climate zones. For example, operating the range hood at the highest exhaust flow rate (680 m^3/h) resulted in an air change rate of 1.65 h^{-1}, which is significantly above the rate without the fan operating. The energy impacts of more effective exhaust ventilation rates highlight the need to balance the benefits of improved indoor air quality, in this case UFP control, with the energy required to achieve these improvements.

4. Conclusions

The present study investigates the effectiveness of a kitchen range hood in reducing indoor levels of UFP emitted from a gas stove and oven. Experiments were carefully designed and conducted in an unoccupied manufactured house to monitor size-resolved UFP (2 nm to 100 nm) concentrations while operating the cooking appliances and range hood. The results show that UFP reduction varies with range hood flow rate, particle size, and burner position. Higher range hood flow rates generally increased UFP reduction within a house, though the effect of the hood flow rate varied with the particle size. At the same exhaust flow rate, lower particle reduction effectiveness was observed for smaller particles, likely due to molecular and turbulent diffusion. With regard to burner position, larger UFP removal was observed for the back burner than for the front burner. Regular and appropriate usage of a kitchen range hood during cooking activities can potentially reduce UFP concentrations; however, decisions about the design and use of kitchen exhaust hoods for controlling UFP and other combustion contaminants require consideration of both the indoor air quality improvements and energy costs.

Disclaimer: The full description of the procedures used in this paper requires the identification of certain commercial products and their suppliers. The inclusion of such information should in no way be construed as indicating that such products or suppliers are endorsed by NIST or are recommended by NIST, or that they are necessarily the best materials, instruments, software, or suppliers for the purposes described.

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