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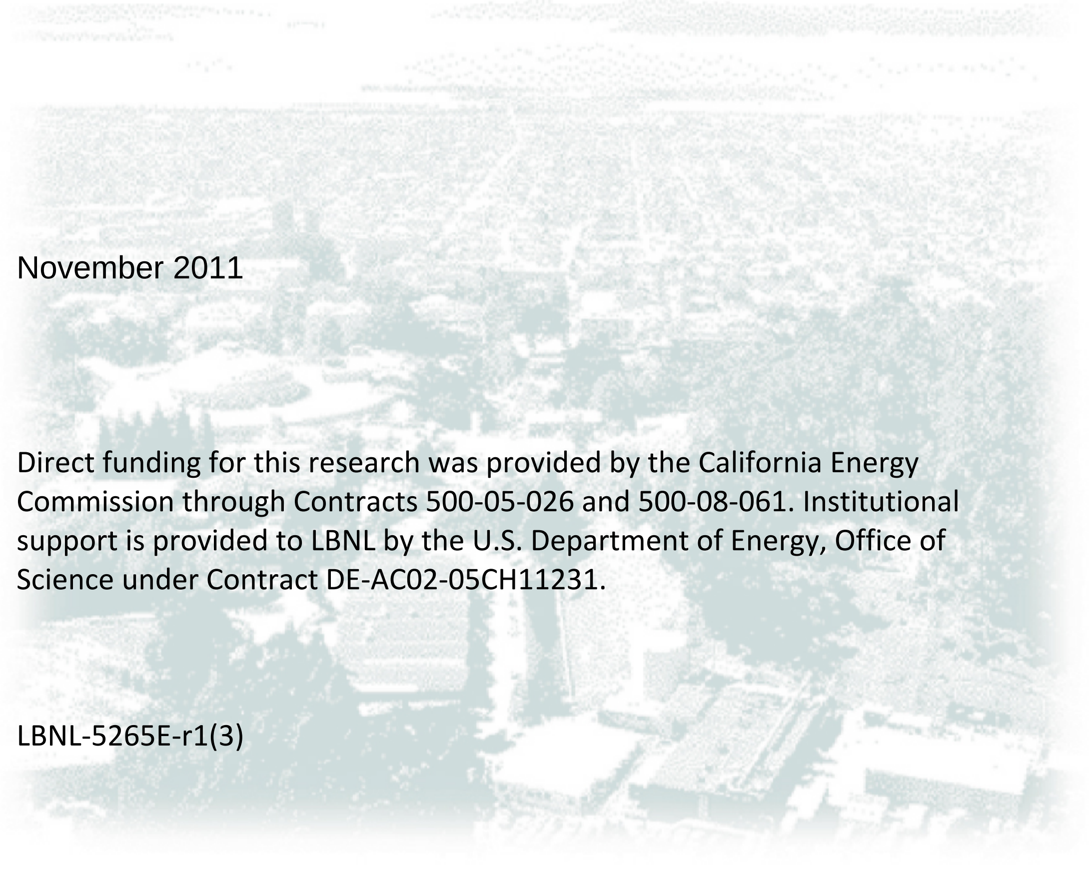

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Abstract

The performance metrics of airflow, sound, and combustion product capture efficiency (CE) were measured for a convenience sample of fifteen cooking exhaust devices, as installed in residences. Results were analyzed to quantify the impact of various device- and installation-dependent parameters on CE. Measured maximum airflows were 70% or lower than values noted on product literature for 10 of the devices. Above-the-cooktop devices with flat bottom surfaces (no capture hood) – including exhaust fan/microwave combination appliances – were found to have much lower CE at similar flow rates, compared to devices with capture hoods. For almost all exhaust devices and especially for rear-mounted downdraft exhaust and microwaves, CE was substantially higher for back compared with front burner use. Flow rate, and the extent to which the exhaust device extends over the burners that are in use, also had a large effect on CE. A flow rate of 95 liters per second (200 cubic feet per minute) was necessary, but not sufficient, to attain capture efficiency in excess of 75% for the front burners. A-weighted sound levels in kitchens exceeded 56 dB when operating at the highest fan setting for all 14 devices evaluated for sound performance.

Key Words

Carbon monoxide; Natural gas burners; Nitrogen dioxide; Range hood; Task ventilation; Unvented combustion.

Practical Implications

Natural gas cooking burners and many cooking activities emit pollutants that can reach hazardous levels in homes. Venting range hoods and other cooking exhaust fans are thought to provide adequate protection when used. This study demonstrates that airflows of installed devices are often below advertised values and that less than half of the pollutants emitted by gas cooking burners are removed during many operational conditions. For many devices, achieving capture efficiencies that approach or exceed 75% requires operation at settings that produce prohibitive noise levels. While users can improve performance by preferentially using back burners, results suggest the need for improvements in hood designs to achieve high pollutant capture efficiencies at acceptable noise levels.

Citation

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Disclaimer

Introduction

Effective removal of air contaminants generated inside residences is needed to provide good indoor air quality and to protect the health and safety of occupants. Unvented gas appliances, including stovetops and ovens, can emit substantial quantities of carbon monoxide, nitrogen dioxide, formaldehyde and ultrafine particles (Dennekamp et al. 2001; Moschandreas and Relwani 1989; Singer et al. 2009; Traynor et al. 1996). Cooking activities (e.g. frying, grilling, and baking) contribute additional pollutants, odors and potentially undesirable levels of water vapor to indoor air (Fortmann et al. 2001). Cooking exhaust fans – including above the cooktop range hoods and downdraft systems – can remove burner exhaust and cooking-related contaminants before they mix throughout the home (Fugler 1989; Revzan 1986; Rim et al. 2011; Singer et al. 2011a; Singer et al. 2011b).

There are several relevant criteria for assessing cooking exhaust system performance. Primary among these is the efficiency at which contaminants generated on the cooktop and in the oven are exhausted before mixing into room air. Airflow, sound levels, and power consumption are also important performance parameters. While there is currently no rating system for capture efficiency of residential cooking exhaust devices, standard test methods and metrics exist for airflow, sound, and power consumption.

Airflow is expected from basic physical considerations to have a substantial impact on capture efficiency. The Home Ventilating Institute (HVI) certifies and publishes performance ratings for residential ventilation equipment, including cooking exhaust fans (HVI 2009a, 2010). HVI provides guidance on “minimum” (min.) and “recommended” (rec.) exhaust hood airflow rates in units of cubic feet per minute of airflow (cfm) per linear foot (lf) of cooking appliance width (HVI 2008). The guidance values are translated here to units of liters per second (lps) per linear meter (lm) using the conversion of 1.55 lps/lm per cfm/lf. The guidance values are 62 lps/lm min. and 155 lps/lm rec. for an appliance against a wall and 77 lps/lm min. and 232 lps/lm rec. for an island installation. For a U.S.-standard 30-inch (76.2 cm) wide range, these translate to 47 lps (100 cfm) min. and 118 lps (250 cfm) rec. for a wall installation and 59 lps (125 cfm) min., 177 lps (375 cfm) rec. for an island.

The level of sound produced during use is an important usability criterion. Though not definitive due to small sample sizes, restricted demographics, and self-reporting, the available data suggest that in the United States only about 10-25% of households always use their range hood while cooking, 40-60% use a hood sometimes, and 20-30% report never using their hood (Klug et al. 2011; Parrott et al. 2003; Price and Sherman 2006; Wilson et al. 1994). Excessive noise is one of the most cited reasons for avoiding routine use of cooking exhaust fans. HVI has a standard method for certifying sound levels (HVI 2009b).

In this work we investigate the extent to which cooking exhaust devices, if used, are effective at removing pollutants formed during combustion, and to what extent the effectiveness varies with airflow rate, device characteristics, and burner selection.

Methods

On-site performance evaluations were conducted for an opportunity sample of 15 cooking exhaust systems installed in California residences. The sample included two downdraft exhaust units, two exhaust fan / microwave over-the-range (OTR) appliances, three installations of the same model of under-cabinet system with no substantial collection hood and grease screens covering the bottom inlet, and eight units with collection hoods. Comprising these eight were two island chimney units, one wall-mount chimney unit, and five under-cabinet units. The sample included three units installed at the time the kitchen was built, six units installed as part of a major kitchen remodel, two units installed by the current homeowners to replace a previously installed device, and four units installed by current homeowners into a kitchen that did not previously have an exhaust fan. Eight of the 13 above-the-cooktop devices were installed at heights consistent with product and/or industry recommendations, while others were slightly above or below the recommended height. The downdraft systems are incorporated into the cooking appliances. Details about experimental methods and photographs of the installed exhaust devices can be found in (Singer et al. 2011a).

Airflow

Airflow rates were measured using two approaches. Initially, airflow rates for F3, B2, and H2 were quantified by releasing sulfur hexafluoride tracer at a known rate into the hood intake and measuring concentrations downstream, and airflow rates for H2 and all other hoods were measured with a calibrated flow hood method described in detail by (Walker et al. 2001). With each method, the fan was operated through all settings, starting with the highest then stepping through to lower settings. The fan was not turned off between experiments in most cases. When laboratory experiments conducted subsequent to those described in this paper (Singer et al. 2011b) showed that microwave hoods may draw air from a second location above the microwave oven door, in addition to the primary pathway at the bottom of the microwave, we used the tracer method to (re-)measure total exhaust airflow through units F1 and F2.

Capture Efficiency

In the present paper, the primary metric for exhaust device effectiveness is “capture efficiency,” used by (Li and Delsante 1996; Li et al. 1997) and others to quantify the fraction of generated pollutants that are pulled directly into the range hood before mixing into room air. Specifically, we quantify pollutant removal in terms of single-pass capture efficiency (SPCE), defined as the potentially time-varying fraction of pollutant mass emitted from the cooking appliance that is drawn directly into the exhaust system, i.e., before mixing into bulk room air.

The concentration of a pollutant P moving through the exhaust device, $C_{P,h}(t)$ (ppm or mL m^{-3}), can be measured directly and related to other parameters using the mass balance shown below:

$$Q_h\,[C_{P,h}(t) - C_{P,r}(t)] = \eta_D(t)\,E_p \tag{1}$$

Here Q_h (m^3 min^{-1}) is the airflow rate through the exhaust system; $C_{P,r}(t)$ (mL m^{-3}, or ppm) is the concentration of P in the room air entering the diluted burner exhaust plume; $\eta_D(t)$ is the time-dependent capture efficiency; and E_P (mL min^{-1}) is the emission rate of P. The use of a time-varying room air concentration allows for an increase in this value resulting from emitted mass that is not captured on the first pass.

In the experiments conducted for this study, CO_2 was used as the marker for burner pollutants. The CO_2 mass emission rate was calculated from stoichiometry assuming complete combustion. The production rate of CO_2 (E_{CO2}) was calculated as follows:

$$E_{CO2} = Q_{fuel}\,N \tag{2}$$

where E_{CO2} is the emission rate of CO_2 (mL h^{-1}), Q_{fuel} is fuel flow rate (mL h^{-1}), and N is the molar fraction of carbon in the fuel (mol C per mol fuel), based on fuel composition. The fuel flow rate for each configuration of burners was checked using the home gas meter – taking care to subtract baseline fuel use for pilot lights, etc. – and when possible checked for consistency against the burner firing rates shown on the cooking appliance label. For all experiments, we used a value of N = 1.0246 for a representative Northern California fuel with 95% methane, 3% ethane, 0.2% propane, 0.9% carbon dioxide, 0.9% nitrogen (Singer et al., 2009). Based on our experience in conducting experiments with cooktops as described in Singer et al. (2009), we estimate that the incomplete combustion assumption and uncertainties in fuel flow measurement contribute <1% and up to about 5% respectively in the uncertainty of calculated capture efficiencies.

The concentration of CO_2 in the exhaust stream was measured with an EGM-4 infrared analyzer (PP Systems, ppsystems.com) that sampled either from the exhaust discharge or at a point as far downstream from the exhaust inlet as could be achieved. The analyzer has a rated accuracy of better than 1 percent of the span concentration over the calibrated range. The span calibration was checked at each experimental site with a verified standard mixture of 2,532 ppm CO_2. The concentration of CO_2 in room air was determined from measurements in the exhaust air before and just after each burner firing.

In all but one case, airflow measurements and capture efficiency experiments were conducted on the exhaust systems as found, i.e. without cleaning or replacement of grease screens. Three of the hoods had no inline grease screens by design, relying instead on impaction for grease collection. Among systems containing grease screens, most were lightly soiled with loading that did not appear to present a substantial incremental impairment to airflow. For exhaust system F2 (a microwave exhaust fan), the grease screen was found with a thick mat of accumulated grease and dust. The grease screen for this system was cleaned using dish soap and hot water and replaced in the hood before the experiment.

All cooktop experiments were conducted with covered 23-cm diameter, 5-L stainless steel pots filled with 3-4 L of room temperature water placed on each burner being used. The pots provided a physical barrier that somewhat cooled the plume of hot exhaust gases and forced the plume radially out from the center of each burner. Between experiments, pots were cooled to room temperature or slightly higher by exchanging water and through rotation. For oven experiments, the oven was set to 232 °C to ensure that the burner would operate for at least 5 min.

Capture efficiency experiments generally were conducted first at the highest fan setting, then at decreasing fan settings. The intent was to minimize buildup of CO_2 in room air resulting from incomplete capture. The exhaust fan generally remained on throughout each set of experiments.

Experiments were conducted with one of four burner configurations: oven only, single front cooktop burner, single rear cooktop burner, combination of one front and one rear cooktop burner. In almost all two-burner cases, the burners were diagonally opposed. In most homes, all four of these configurations were evaluated at both the lowest and highest fan settings. Some configurations were evaluated at intermediate settings.

In most experiments, we attempted to minimize external drivers of airflow in the vicinity of the cooking appliance. Adjacent windows were closed and the researcher avoided activity nearby to the cooktop. In a few experiments, the field researcher explored the effect of human activity by walking up to the cooktop once per minute, standing and stirring the pot of water for 30 seconds, then walking away. Results of these experiments are presented in Singer et al. (2011a).

Sound

The “sone” is a unit of sound intensity that is intended to relate to the perceived loudness of a sound. Since sones cannot be readily measured in field experiments, we quantified a related quantity: frequency-weighted sound levels, using the so-called “A-weighting” (dB-A). This is a standard approach for monitoring environmental and industrial noise containing multiple frequencies. We measured dB(A) with an Extech 407736 digital sound meter. Measurements were made at a standard position in front of the range/oven and at another location likely to be occupied in the kitchen (e.g., at a table or a food preparation area). The front of range position was 150 cm above the kitchen floor and 25 cm from the front of the range. Sound levels at both locations were measured under background conditions and for one or more fan settings. Background sound levels were measured with the exhaust fan off and without other experimental equipment operating. For some exhaust fans, the sound measurements were made subsequent to airflow and capture efficiency experiments.

Device and Installation Characteristics

The evaluated exhaust systems are divided into 4 basic design types. The most substantial distinction is between downdraft and above the range systems. Above the range devices are subdivided into units that feature a true capture hood or inverted “bowl” (identified as B1-B6); devices that provide minimal or no capture volume, having a “flat” profile (identified as F1-F5) and “hybrid” devices with a substantial capture volume above grease screens that cover the bottom inlet (H1-H2). The grease screens at the bottom of the hybrid units can impede vertical airflow even when clean and certainly when coated with grease and dust. The same impediment can occur on “bowl” units that have air inlets covered with grease screens.

For marketing purposes, cooking exhaust devices are organized into the following categories: under-cabinet (largest and broadest category); microwave-exhaust combination units (typically marketed as microwaves but including ventilation systems); chimney – wall; chimney – island; and downdraft. In our study, devices D1 and D2 are variations of the same basic design and nameplate of downdraft exhaust units; both draw air from behind the rear burners. Devices F1 and F2 are exhaust fans built into over-the-range (OTR) microwave ovens. Devices F3-F5 are essentially the same model of under-cabinet device installed in different configurations: F3 has no cabinets on either side of it, F4 has a cabinet on one side, and F5 has a cabinet on one side and a refrigerator on the other. Devices B3 and B6 are mounted above island cooktops. All of the other units are mounted between cabinets, although H1 has some space between the unit and the cabinets on either side. Units B3, B5 and B6 all contain the same fan unit.

Table 1 provides information about the devices evaluated. The devices spanned a wide range of prices and nominal airflows. Same or comparable new versions of the evaluated exhaust devices span a retail price range of under \$100 to roughly \$3000. While the total cost of the microwave units is listed as \$300, this cost includes a microwave oven; the exhaust fan component of this appliance typically is of lower cost and quality. Additional information about the devices is available in Singer et al. (2011a).

Recommended installation height above the cooking surface varied from 33–53 cm (13–21 in.) for B4 to 76–91 cm (30–36 in.) specified for H2. In general, the larger open hoods (B3, B5, B6) and “hybrid” units with large collection hoods above the bottom grease screens allow higher installations. A higher installation has less potential to interfere with cooking. Microwave units balance the objectives of mitigating obtrusiveness (e.g. through limited projection over front burners) and convenient access to the microwave, which requires that the appliance not be too high above the range. Most above the range systems in our study were installed within the recommended height range or just slightly above it. The largest deviation between recommended and actual was observed for F3, with an installed height of 99 cm (39 in.) and a recommended range of 41–58 cm (16-23 in.).

Table 1 additionally provides information about the fraction of the cooktop covered by the exhaust appliance. For each device, “cooktop coverage” was assessed as the fraction of burner area – defined by the grates over each burner – that was covered by the exhaust device. Cooktop coverage reported in Table 1 is for all four cooktop burners. Coverage of over the range exhaust systems exceeded 75% of cooktop burner area for eight of the units, was in the range of 50-75% for three units and was <50% for two installations. Interestingly, the sample includes examples of the same exhaust hood installed at similar heights but with very poor (F4) and very good (F5) cooktop coverage. Seven of the eight open and hybrid systems had cooktop coverage in excess of 75%. In all cases of incomplete cooktop coverage the front burners were not completely under the exhaust device. In two cases (devices F1 and F4) even the rear burners were not completely covered; these exhaust systems were set flush with the rear wall and the cooking range was set several inches out from the wall.

Later discussion of the effect of coverage on capture efficiency considers the extent to which the exhaust device sits directly over the burners that were actually in use for each experiment. We use the term “in-use burner coverage” to distinguish this from “cooktop coverage.” Most devices had full coverage over the rear burners, and therefore had good in-use burner coverage for experiments that used rear burners only.

Multivariate Analysis

The influences of airflow rate and other parameters on capture efficiency were analyzed using multivariate regression. Indicator variables were created for each of the modeled device types (Bowl, Hybrid, Flat). Indicator variables were also created for each burner combination (Rear only, Front and Rear, or Front Only) and for the degree of in-use burner coverage (<50%, 50-75%, >75%). For instance, in a test that used both a back burner and a front burner, coverage was “good” if the device extended over the rear burner and more than half of the front burner, “fair” if it extended over the back burner and less than half of the front burner, and “poor” if it covered only the rear burner (or less). Coverage was good for all rear burner experiments.

Results and Discussion

Airflow

Measured airflows at various fan settings are presented in Table 2. (Table 2 also includes sound measurement results that are discussed later.) Measured airflows ranged from 35 to 180 lps (74 to 382 cfm) at the highest fan settings. The airflow rates as well as the ratio of airflows across settings varied substantially among the units evaluated. Higher-cost units tended to have higher airflows. However, the modestly priced F2-F5 and B4 ($300 and under) all had flows in the range of 105-120 lps (230-250 cfm) and H2 ($450) had among the highest airflows, moving about 70 lps (150 cfm) on low and about 170 lps (360 cfm) on high setting. For some devices the different settings covered only a narrow range of flow rates. For example, device F2 was tested with four fan settings, from “Low” to “Boost”, but the flow rates for these settings only varied from 102 to 120 lps (217 cfm to 255 cfm).

The ratio of measured to nominal (nameplate or manufacturer specified) airflow at the highest fan setting ranged from a high of 100% to a low of 28%. Four of the six HVI-rated units (representing two models, as F3-F5 are all the same model) had maximum airflows within 90% of the nominal values. A third model had maximum airflow of 71% of nominal and the fourth model was below 50%. The lowest performing of the HVI-rated systems was an older (>15 years) economy hood (B1). Of the nine units that were not HVI-rated, only three had maximum airflows that were greater than 50% of the nominal values and two of these were high-end products costing above $1000. The low-cost F1 unit had low airflow even on its high setting, but the similarly inexpensive F2 had much higher airflow. The substantially more expensive B2 and B3 did not achieve expected (nominal) airflow values. The nominal airflows noted for D1 and D2 were taken from the product literature for the fans installed in these units; this value appears to represent fan free-air delivery and does not even account for the pressure drop that results when the fan is installed into the downdraft appliance.

Capture Efficiency

Figure 1 shows capture efficiency for all experiments conducted with each exhaust system. It is apparent from Figure 1 that capture efficiency varies widely across the range of installed devices and conditions evaluated. For many devices there are very clear differences in performance related to burner selection and airflow. As the vast majority of experiments were conducted without interfering with airflow around the hood area, these results should be considered as best case conditions for these particular devices. Individual capture efficiency data points are estimated to be within 15-20% (on a relative basis) of the true, average value for the condition. This includes estimated uncertainties of up to 5% each for airflow, fuel flow, and incremental CO_2 measurements with additional but unevaluated uncertainty resulting from real trial-to-trial variability in exhaust hood airflow and capture efficiency performance.

Figure 2 presents the same data in a manner designed to display variations in capture efficiency by device type, airflow, burner selection, and the extent to which the device extends over the burners that are in use. Within each panel, capture efficiency is plotted against airflow. Panels show different combinations of burner configurations (columns) and device type (rows). Plotting symbols are the same as in Figure 1. Colors indicate different categories of in-use burner coverage. Dashed lines in the plots show predictions from a linear model that was fit to data from all of the devices except the downdraft types.

We used multivariate linear regression analysis to investigate the extent to which capture efficiency can be predicted from various combinations of explanatory variables. Predicting capture efficiency using linear regression is not correct on theoretical grounds. First, the efficiency can never be less than 0 or greater than 100%, but the prediction can. Second, the efficiency must go to zero as airflow goes to zero, but forcing this to be the case by using a no-intercept model generates poor fits. Alternatives to untransformed linear regression were considered and in some cases explored, but a nonlinear fit or a fit to transformed variables is much harder to interpret. Ordinary linear regression to predict capture efficiency yields easily interpretable results that fit well over the range of airflows observed in this study, but the results cannot be used to predict efficiency for very low or high flow rates. Also, the model results apply to the units as they were found, and cannot be used to predict how these units would behave if they were installed differently, such as with different configurations of adjacent cabinets and countertops.

In some of the regressions, indicator variables were used for device type (bowl, hybrid, or flat) and/or for different combinations of burners in use. In each case, these were implemented as separate indicator variables for each type or combination. For instance, a "bowl" indicator variable took the value 0 for non-bowl devices and 1 for bowl-type devices.

Regression results are presented in Table 3. To illustrate the use of this table, consider using model 7 to predict the capture efficiency for a particular situation: a Flat device, operating at a flow rate of 106 lps (225 cfm), with one front burner in use, and poor coverage of the front burner. Referring to line 7 in Table 3, we calculate 28 + 33*1.06 -6-18=39, so model 7 predicts an efficiency of about 39% for this situation, with an uncertainty (one standard error) of 14 percentage points. In fact, two of the experiments met this general description: a test of device F3 at a flow of 109 lps (231 cfm) yielded a capture efficiency of 28%, and a test of device F4 at a flow of 115 lps (244 cfm) yielded a capture efficiency of 21%.

Comparing models 6 and 7, we see that including indicator variables for the burners used, and including in-use burner coverage as well, yields only slightly better results (higher R^2, lower RSE) than including only the indicator variables for which burners were used, as long as device type is also included. However, the effect of in-use burner coverage is undeniably (and unsurprisingly) real, with poor coverage corresponding to an estimated 18-point drop in effectiveness, all other things being equal. To put that in perspective, an exhaust device with poor in-use burner coverage would have to provide an extra 52 lps (110 cfm) of airflow in order to be as effective as a similar type of device with fair or good coverage.

Line 1 of the table shows that Bowl and Hybrid devices performed about 25 percentage points better than Flat devices in removal efficiency; but, as Model 7 shows, the difference is reduced to about 15 percentage points when coverage and flow rate are taken into account. Flow rate is, as expected, very important, with each 50 lps (106 cfm) increase in flow corresponding to about a 15 percentage point increase in capture efficiency. All of the models summarized in Table 3 assume that the dependence of capture efficiency on flow rate is the same for all device types, as is the dependence on which burners were used, and on the coverage of the device.That is why there are only 9 coefficient estimates for Model 7, rather than the 56 that would be required to do a separate fit for each combination of device, airflow, and in-use burner coverage.

Different relationships surely hold for different device types, but with such small numbers of devices of each type it is not possible to get accurate parameter estimates by modeling each type separately. Model 7 predictions are displayed in Figure 2 for good coverage (green dashed line, which is upper-most), fair coverage (blue) and poor coverage (red, lower dashed line). Compare red lines to red symbols, blue to blue, and green to green. From the definition of model 7, all of the prediction lines have the same slope as a function of airflow, and all have the same downward offset associated with poor coverage; lines are shifted upwards or downwards according to the coefficient associated with the device (row) and the burners used (column).

Predictions for fair or poor coverage are not shown for back burners or oven, because all devices provide good coverage for these cases.

Model 7 explains about 70% of the variance in measured capture efficiencies. Sources of variation that are not included in the statistical models include: (1) device design features that are not captured simply by categorizing the devices into Bowl, Hybrid, or Flat; (2) installation features, such as whether adjacent appliances or walls help to guide air towards the fans; and (3) model misspecification, such as the fact that capture efficiency cannot in fact be linear in flow, as it is in the models.

Five of the thirteen non-downdraft devices behave substantially differently from the predictions from model 7: Devices B1 and B6 perform about 13 percentage points worse than predicted; F4 performs about 22 percentage points worse than predicted; B2 and F2 perform around 15 and 20 percentage points better than predicted. All of these differences are highly statistically significant; however, the prediction for B6 is for 100% efficiency so this device was guaranteed to underperform the prediction. For the other eight above the cooktop devices, the average capture efficiency is within 10 percentage points of the model predictions. The results for the anomalous devices other than B6 may be due to the situations in which they are installed. Photographs of the devices and their installation details can be found in Singer et al. (2011a). Device B1 and the stovetop under it are next to a doorway, not next to cabinets or at countertops as are most of the other devices; this may influence the airflow so as to decrease the amount of capture. In contrast, cabinets extend downwards towards the stovetop on both sides of device B2, which may help with capture. On the other hand, cabinets also extend downwards on both sides of H1, but that device performs only as well as the model predicts. Overall it appears that installation details, beyond simply the amount of coverage of the front burners, may promote or inhibit capture efficiency by as much as fifteen percentage points.

We also looked for systematic variation with the installation height – we tried using the height of the device over the cooking surface, and also height above the maximum recommended height as explanatory variables – but the resulting coefficient estimates were within one standard error of 0 and did not substantially improve the fits. The null finding for height is based on a limited sample of hoods and heights; height could be relevant for hoods or installation heights beyond those observed in this study. We also fit a variety of mixed-effects models (as described in (Gelman and Hill 2007)), with individual device coefficients as random effects, but the minor improvement in the predictions is not worth the added complexity of the models.

Performance degradation with equipment age could not be assessed with this small, disparate sample and likely varies considerably with device quality, cooking activity patterns and other factors. We note, however, that the 15 year-old B2 achieved capture efficiencies toward the top of the Bowl group despite having lower airflow than some other, newer devices in the group (Figures 1-2). This indicates that good performance is not necessarily compromised with age.

Sound

The primary goal of the present paper is to provide insight into the effectiveness with which kitchen exhaust devices remove pollutants generated during cooking, and the extent to which the effectiveness varies with features of the devices and the situations in which they are installed. However, any device is effective only when it is being used, and many people say noise is a deterrent to using their exhaust fan (Nagda et al. 1989; Parrott et al. 2003). We measured sound levels to document this important performance element.

Table 2 presents summary results for measured sound levels at the cooktop for 14 of the 15 installations. Sound levels elsewhere in the kitchen are presented in Singer et al. (2011a). Background sound levels varied from 34 to 49 dB(A) and increased to 57 to 71 dB(A) with exhaust fans operating on the highest settings. Even on medium or low fan settings many devices, coupled with the ambient noise already present, raised sound levels above 60 dB, a level that would strongly compete with normal conversation. Given these results it is not surprising that people are reluctant to use their exhaust devices.

The sound numbers in Table 2 show total measured sound levels, which includes both ambient noise and noise from the exhaust device. The sound level for the device alone can be determined by using the appropriate equation for subtracting sound levels (Davis and Davis 1997):

$$D = 10\log_{10}(10^{T/10} - 10^{A/10}) \qquad (3)$$

where D is the noise level created by the device, A is the ambient noise level (i.e. the sound level measured with the the device turned off), and T is the total noise level when the device is turned on. Figure 3 shows device sound level (at the front of the cooktop) versus airflow for each measured airflow. Sound levels are extremely variable at low flow rates – some devices are very noisy even at quite low flow. Among the tested devices and fan settings that were effective at removing pollutants for all burner combinations, only H2 (filled triangles) on its medium fan setting was fairly quiet. Still, this device at least proves that a fairly quiet, effective device is possible. The extremely effective B6 device (X symbol) was fairly loud, but still quieter than many competing devices that moved much less air; potentially, a device like B6 operated at a lower airflow could be both quiet and at least moderately effective.

Product literature specified sound levels (in sones) for three fan settings of H1, for high and low fan settings of F3–F5 (variations of the same device), and for the highest fan settings of B1 and B3–B6. Among these devices and settings, the lowest specified sound levels were 0.9 sones for F3–F5 on low fan setting. This setting produced the lowest measured device-generated noise levels: 37 and 41 dB(A) for F3 and F5, respectively. The other devices and settings had sound specifications ranging from 2.0 to 6.0 sones and device-generated sound measurements of 57–71 dB(A) with an R^2=0.53.

It is important to note that the performance measurements reported in this study may reflect installation elements that were not assessed in this study. Improper device installation or ductwork can directly impact sound and airflow, and indirectly impact capture efficiency. The effect of such installation parameters is worthy of future study.

Conclusions

For any given device, higher airflow generally leads to higher capture efficiency, with each 100 lps increase in airflow increasing the capture efficiency by about 33 percentage points. However, at a given airflow there is a great deal of variation in capture efficiency among devices, and meeting industry standard guidance on minimum airflow requirements is not sufficient to ensure removal of most of the pollution generated by cooking.

The results of this limited study suggest that the most effective designs are those that include a capture volume and a robust fan. While the most effective devices (B5 and B6) are relatively expensive, the more moderately priced devices H2 and B4 also had high capture efficiencies under almost all conditions. B2 also performed well.

Whether the exhaust device extends over the burners being used also has a large influence: a device that does not cover the in-use burners suffers a very large penalty in capture efficiency, of 20-25 percentage points. As a consequence, for many of the under-cabinet and wall mount units (and for the back mounted downdraft systems), capture efficiencies were much higher on back as compared with front burners. In many cases, cooking on the rear burner with the fan on its low setting is as effective or more effective than cooking on the front burner with the fan on its medium setting.

The flat-bottom models in the study suffer from three problems: poor coverage of the front burners, low flow rates, and lack of physical features that would funnel pollutants towards the fan. The combined effect of these problems can be quite substantial: with the front burner in use, a flat device with poor coverage of the front burner and a weak fan can be expected to perform about 45 percentage points worse in removal efficiency than a hybrid or bowl device with good coverage and a fan that moves an extra 50 lps.

The devices with highest capture efficiency – F2, H2, B2, B4, B5, and B6 – remove more than 75% of cooking pollution when operated at medium fan setting or higher. To use these devices requires willingness to tolerate a moderately noisy kitchen, since all of these devices except H2 generate at least 60 dB of sound intensity at a medium fan setting or higher. Device H2 indicates that an effective, fairly quiet device is possible.

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Table 1. Characteristics of cooking exhaust fans evaluated in this study.

Device Characteristics (NA = not available; NR = not relevant)							Installation	
ID	Age (y)	Est. Cost [a]	Nominal airflow (lps) [b]	Number of fan settings	Sound (sones) [b]	Rec. height (cm) [b]	Installed Height (cm)	Cooktop Coverage [c]
				Downdraft				
D1	10	$1,350	283 [e]	4	NA [d]	NR [d]	NR [d]	NR [d]
D2	15+	$1,350	283 [e]	3	NA [d]	NR [d]	NR [d]	NR [d]
				Flat (No capture hood)				
F1	4	$300 [f]	142	5	NA [d]	>36	57	<50%
F2	4	$300 [f]	142	5	NA [d]	>36	48	50-75%
F3	9	$275	118	3	3.5	41–58	99	50-75%
F4	6	$275	118	3	3.5	41–58	64	<50%
F5	5	$275	118	3	3.5	41–58	69	>75%
				Hybrid (Capture volume above bottom grease screens)				
H1	3	$825	359 [e]	4	4.5	66–76	81	>75%
H2	5	$450	170	3	NA [d]	76–91	76	>75%
				Open (Bowl)				
B1	15+	$75	90	2	6	46–61	58	50-75%
B2	15	$950	283 [e]	Variable [g]	NA [d]	64	61	>75%
B3	6	$2,900	260 [e]	1	6	76	69	>75%
B4	8	$300	170	Variable [g]	5.5	33–53	69	>75%
B5	3	$1,250	260 [e]	2	6.5	69	69	>75%
B6	6	$2,900	260 [e]	1	6	76	65	>100%

[a] Estimated retail prices based on review of web-based retailers conducted in late 2009.

[b] Nominal (maximum) airflow provided in product literature as cubic feet per minute; sound and recommended installation height (inches) based on product literature.

[c] Fraction of cooktop covered by range hood.

[d] NA = not available; NR = not relevant to product design.

[e] Fan free air delivery.

[f] F1 and F2 are combined exhaust and microwave over the range (OTR) appliances. The quoted cost includes the cost of the microwave. The exhaust device adds less than $100, based on comparison to the cost of a microwave alone.

[g] Knob or control without any set levels.

Table 2: Airflow and Sound Measurements

Hood	Airflow (lps)[a]				Measured Sound (dB(A))[b]			
ID	Low	Med	High	Nominal	Off	Low	Med	High
D1	101	110	114	283	45	64	66	67
D2	NM	120	136	283	36	NM	55	58
F1	23	44	67	142	43	51	56	61
F2	102	109	120	142	49	63	66	66
F3	24	74	108	118	36	40	47	57
F4	40	NM	116	118	NM	NM	NM	NM
F5	42	77	117	118	34	42	53	63
H1	85	94	106	359	42	62	64	67
H2	72	111	170	170	44	53	56	66
B1	21	NM	35	90	45	73	NA	65
B2	75	78	85	283	43	71	69	68
B3	NM	NM	105	260	42	NA	NA	67
B4	42	97	120	170	41	45	60	65
B5	120	NM	148	260	37	67	NA	71
B6	NM	NM	180	260	34	NA	NA	62

[a] Values shown are means of all measurements recorded. For devices with more than 3 settings, airflow and sound were measured at highest, lowest and one intermediate setting. For fans with fewer than 3 settings, some entries are not applicable (NA). Airflow not measured (NM) for some cases. Under laboratory conditions, the measurement methods are accurate to within 2-3%. For the conditions of this field study, we estimate an accuracy of 5% or better.

[b] Sound was measured at the front of the cooktop. The values shown represent an average over at least 30 seconds of measurement, with precision of 1 dB(A) or better.

Table 3: Regression coefficients (standard errors), residual standard error (RSE), and R^2, for various models that predict capture efficiency (percentage points) based on the following variables: indicator for device type; flow in hundreds of lps; indicator for burner combinations (default is rear burner only); and indicator for extent of coverage over burners (default is >75%). Downdraft devices were not included.

#	Inter-cept	Bowl	Hybrid	Flat	Flow (100s of lps)	Front and Rear	Front Only	Oven Only	In-use burner Coverage Fair	Poor	RSE	R^2
1		71 (2)	70 (4)	46 (3)							24	0.20
2	22 (3)				40 (2)						18	0.50
3	30 (4)				42 (2)	-12 (4)	-15 (3)	-2 (4)			17	0.55
4	35 (4)				34 (2)				-7 (3)	-26 (3)	16	0.63
5		34 (3)	32 (4)	18 (3)	36 (3)						17	0.57
6		42 (3)	38 (4)	24 (3)	36 (3)	-11 (3)	-15 (3)	3 (3)			15	0.65
7		43 (4)	41 (5)	28 (4)	33 (3)	-9 (4)	-6 (5)	2 (4)	0 (4)	-18 (5)	14	0.69

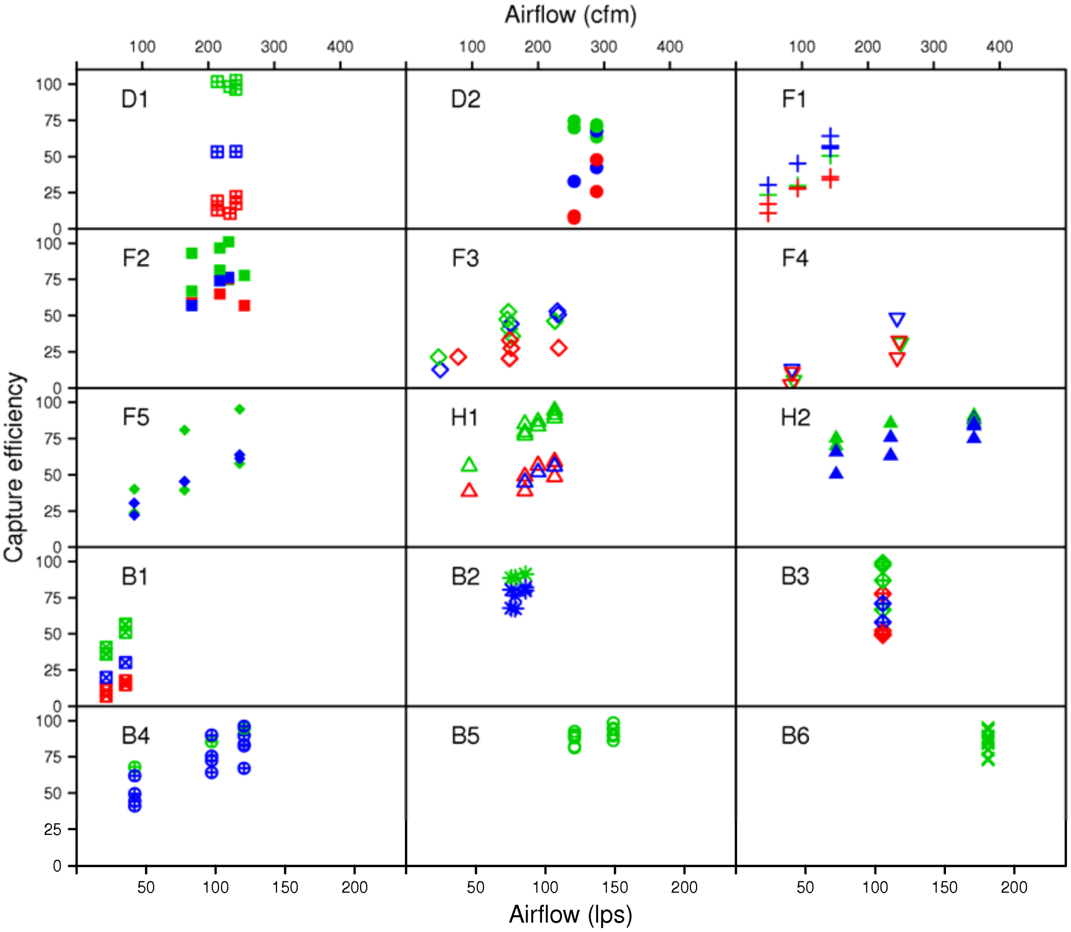

Figure 1: Single Pass Capture Efficiency for each device, for experiments using different fan settings and different combinations of burners. Colors indicate the degree to which the exhaust device extends over the burners that were used: green means >75%, blue means 50-75%, red means <50%. For Downdraft devices, green means a back burner was used, red means front, blue means both. Airflow is shown in liters per second on the lower axis and cubic feet per minute on the upper.

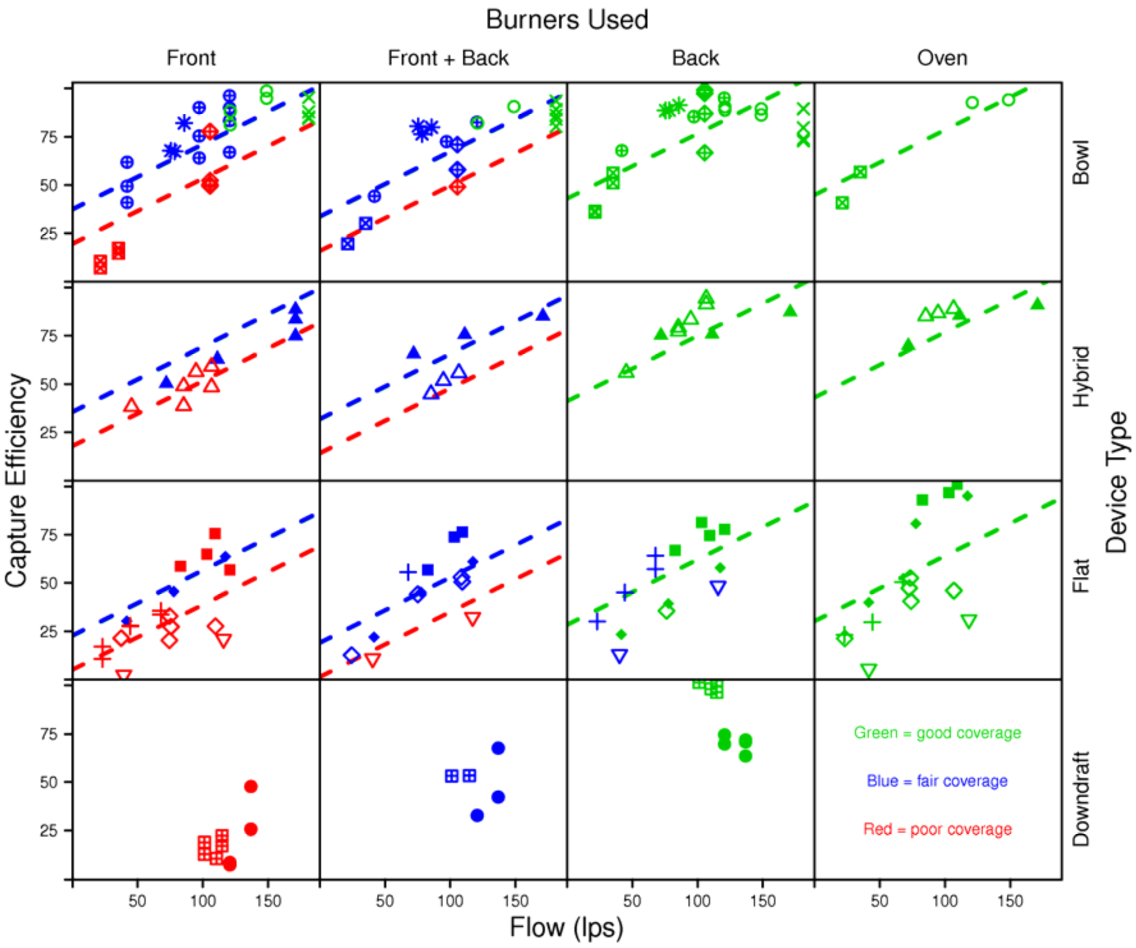

Figure 2: Capture Efficiency versus Flow (lps), for different device types (rows) and various combinations of burner or oven use (columns). The plotting symbols, a different symbol for each device, are the same as in **Figure 1**. Green symbols indicate high in-use burner coverage (>75% of the area of the burners in use is below the exhaust intake), blue indicates medium (50-75%), and red indicates low (<50%). For Downdraft devices, green means a back burner was used, red means front, blue means both. Dashed lines show predictions from model 7, for high, medium, and low in-use burner coverage. Predictions for high and medium coverage are almost identical, so those lines are nearly indistinguishable.

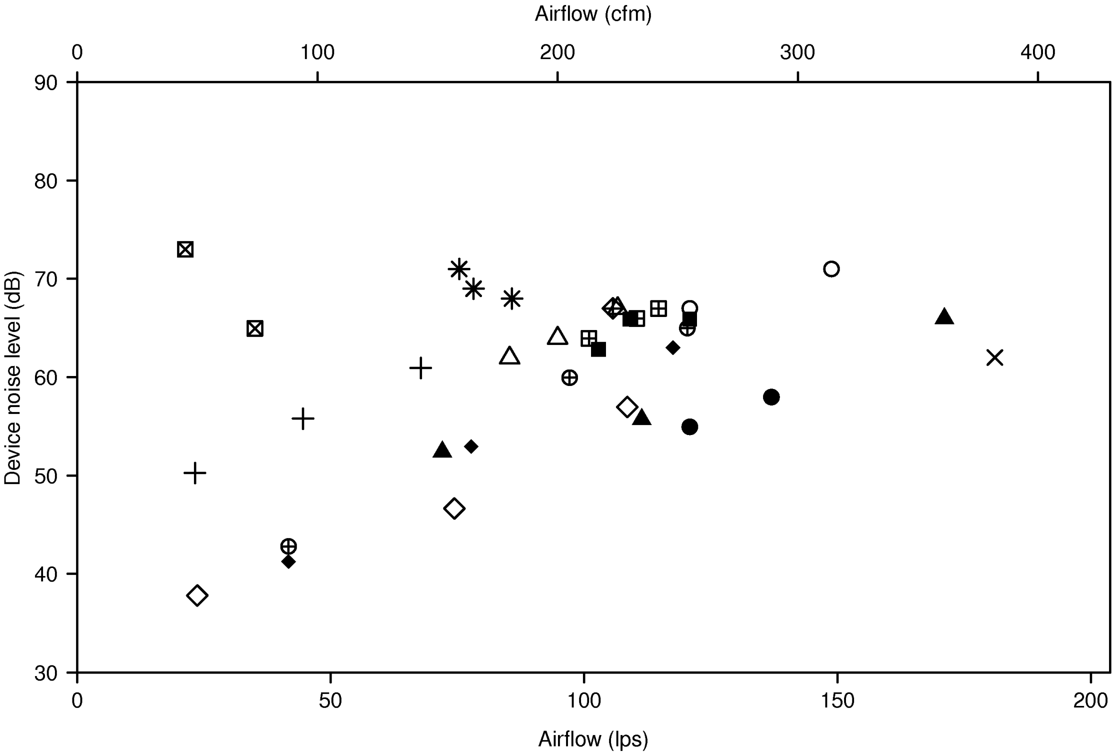

Figure 3: Sound increase over ambient levels versus airflow. A different symbol is used for each device, as indicated in Figure 1.