Technical Memo on Updated Analysis from NO_2 and $PM_{2.5}$ Cooking Simulations to Inform Capture Efficiency Standards

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Introduction

This technical memo presents results of model simulations that were performed since the completion of a recent project sponsored by the California Energy Commission called "Effective Kitchen Ventilation in Net-Zero Energy Homes". The results summarized here followed the same modeling approach described in a report published by Chan et al. in March 2020: "Simulation of short-term exposure to NO_2 and $PM_{2.5}$ to inform capture efficiency standards" (LBNL-2001332).

The first difference between the prior work and these new simulations is that rather than only varying the range hood capture efficiency and using a single range hood airflow, as was done initially, the new simulations include paired capture efficiency and exhaust airflow to determine the overall effect of range hood operation on indoor NO_2 and $PM_{2.5}$ concentrations resulted from cooking.

A second difference is that the results presented in this memo considered a proximity factor to account for higher short-term (average over 1-hour, henceforth 1-h) exposure to emissions from cooking burners, for the person who is in the kitchen and cooking. This effect was not modeled previously when the well-mixed assumption was broadly applied. Here, the model accounts for higher NO_2 in the kitchen when calculating the peak 1-h NO_2 concentration. A proximity factor of 2 was applied to the indoor-generated NO_2 from cooking to account for higher concentrations of the burner-emitted pollutant in the kitchen during and shortly after cooking. In other words, it is assumed that the concentration of NO_2 emitted from the burner is twice as high in the kitchen as it is generally mixed throughout the house. The same proximity factor was used in our previous work (Logue et al. 2014).

Relationship between Capture Efficiency and Range Hood Airflow

The relationship between range hood airflow and capture efficiency (CE) depends on hood design, whether front or back burners are used and the cooking procedure (Singer et al. 2012; Lunden et al. 2015).

Figure 1 shows the relationship determined from LBNL studies (Delp and Singer 2012; Singer et al. 2012; Lunden et al. 2015, Zhao et al. 2020) conducted by placing 5L capacity pots, each filled with 4L of water, on either the front or back burners of gas cooktops. The CE was calculated using measurements of airflow, the CO_2 concentration differences between the room and the range hood exhaust, and the CO_2 emission rate, as described in detail in the cited papers. The CO_2 emission rate was determined by measuring the gas fuel flow rate and calculated from stoichiometry assuming complete combustion.

Figure 1 shows that higher airflow generally translates to higher CE, and CE is higher when using two back burners compared to two front burners. In this analysis, the relationship between capture efficiency and range hood airflow was assumed to follow the one fitted for front burners in Figure 1(a). Since this test procedure measured CE using CO_2, a combustion pollutant, we assume it is representative for NO_2.

An alternative method to measuring CE was described by Kim et al. (2018). That method was developed to be a precisely-repeatable, standard test method and used a steady-state approach, where CO_2 is injected using heated emitters, rather than relying on CO_2 generated from gas combustion. The method specifies emitters which release CO_2 from both the middle, to represent cooking emissions, and the outer circumference to represent gas or electric burner emissions. The approach reported by Kim et al. was developed into ASTM test method E3087. Figure 2 presents CE data reported by Kim et al. (2018) (as green triangles) using the method that was proposed to ASTM and closely reflecting the final approved method. Meleika and Pate (2020) tested five range hoods using the approved ASTM method, but with burner and hood installations that differed somewhat from those used in the experiments of Kim et al. Specifically, Meleika and Pate had emitters placed on top of hot plates on a countertop surface simulating the cooktop base; whereas Kim et al. placed emitters onto heating coils that were at the level of cooktop base. Since the distance between the top of the emitter and range hood was similar in the two studies, in the Melieka and Pate configuration, the range hood was higher relative to the simulated side cabinets, effectively creating partial side panels. Melieka and Pate conducted testing at emitter temperatures of 160C, 130C and 200C. Figure 2 shows the capture efficiency results presented by Meleika and Pate (orange diamonds) as a function of airflow at all three cooktop temperatures.

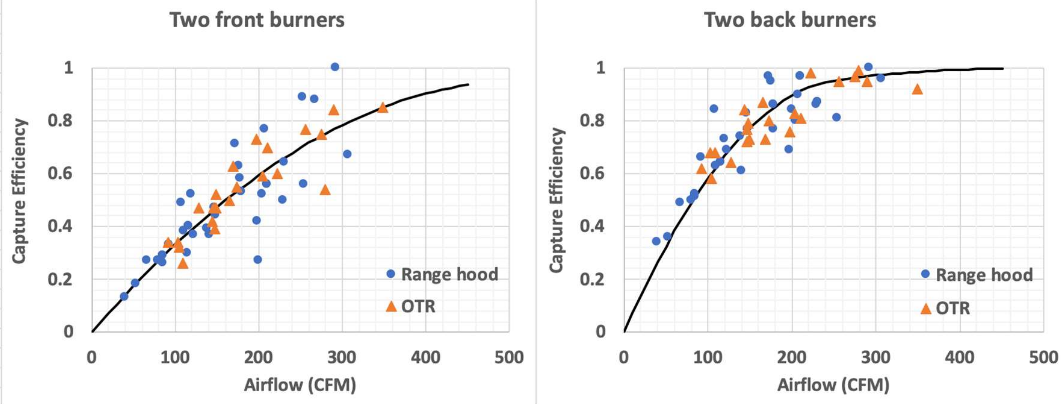

Figure 1. Capture efficiency and range hood airflow from past LBNL studies using a transient method by placing either two pots at the (a) front or (b) back burners. OTR = over-the-range microwave.

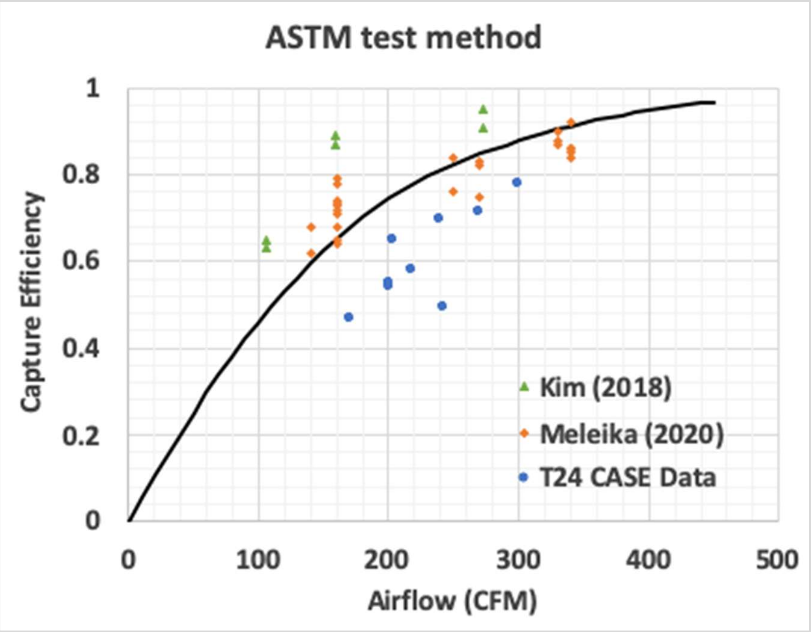

Figure 2 Capture efficiency and range hood airflow determined following the ASTM test method.

Additional testing of capture efficiency and range hood airflow was conducted for Title 24 CASE 2022 cycle using yet another configuration of emitters and range hood placement in relation to the counter and side cabinets These data are the blue circles in Figure 2. Photos of the experimental set-up in the CASE report show that the CO_2 emitters were set into the countertop with their tops at counter level, rather than placed on top of heat plates as the photos shown in Meleika and Pate. These experimental differences may explain why the Title 24 CASE data show lower capture efficiency at a given range hood airflow rate than other tests following the ASTM procedure.

Overall, the ASTM method with CO_2 emitted from both the middle and the outer edge of the emitters shows higher capture efficiency at a given range hood airflow compared to the transient method where natural gas burners were used as the CO_2 source. The ASTM test method is designed to determine the capture of all cooking contaminants from both the source of heat (natural gas or electric coils) and emitted from the cooking process. The data shown in Figure 1 are specifically from emissions of natural gas burners and thus should be considered as specifically more relevant to NO_2 from gas combustion. In this analysis, the relationship between capture efficiency and range hood airflow rate is modeled following the curve drawn using the ASTM method (Figure 2) for $PM_{2.5}$. For natural gas burner emissions, such as NO_2, the relationship between capture efficiency and range hood airflow is modeled using the curve drawn using "two front burners" in Figure 1a.

Results

Provided below are a summary of the results from the updated model runs. Readers are referred to the published report by Chan et al. (2020) for additional details about the modeling.

Table 1 shows the calculated percentage (%) of homes exceeding the 24-hour averaged $PM_{2.5}$ of 25 ug/m^3 threshold from cooking three meals that each have substantial $PM_{2.5}$ emissions in a single day and with the range hood used for each meal. For this analysis we used pairs of CE and airflow determined with the ASTM test and the model also considers $PM_{2.5}$ coming from outside, as described in Chan et al. (2020). The range hood was assumed to reduce emissions into the well-mixed home air volume base on the capture efficiency value used in the simulation. All homes (single-family detached, single-family attached, and multi-family units) were modeled as having base, dwelling unit mechanical ventilation just meeting the requirement of the state's Building Energy Efficiency Standards, with additional airflow from the range hood throughout the assumed cooking duration for each meal. A capture efficiency of 0.50 (50% removal of $PM_{2.5}$ generated at the cooktop) is sufficient to maintain indoor $PM_{2.5}$ below the 24-h threshold value in virtually all homes (>99%) that are larger than 1000 ft^2. Homes smaller than 1000 ft^2 would require higher capture efficiencies (0.55 and 0.65, Table 1) to meet this threshold value.

Table 1. Percent of homes that exceed the $PM_{2.5}$ 24-h threshold value for range hoods with ASTM capture efficiency and modelled airflow rate as drawn in Figure 2.

ASTM Capture Efficiency	Modeled Flow Rate (cfm)	% Homes Exceeding 25 μg/m^3 (WHO)				
		All	<750 ft^2	750 - 1000 ft^2	1000 - 1500 ft^2	>1500 ft^2
0	0	55%	100%	100%	76%	8%
0.50	110	7%	39%	4%	0.3%	0
0.55	130	3%	18%	0.7%	0	0
0.60	140	1%	7%	0.2%	0	0
0.65	160	0.2%	1%	0	0	0
0.70	180	0.01%	0.06%	0	0	0

Higher capture efficiencies are needed to maintain the maximum 1-h averaged NO_2 below the 100-ppb threshold value (Table 2). In this analysis, the home is assumed well-mixed, but a proximity factor of 2 was applied to the NO_2 emitted by the gas burners to account for higher NO_2 in the kitchen when calculating the maximum 1-h concentration. (The factor of 2 for proximity to the emission source is assumed only for the NO_2 emitted from the gas burner, and not applied to NO2 entering from outdoors.) The highest 1-h NO_2 was modeled with outdoor NO_2 data from late afternoon and evening hours because dinner is typically the largest meal in California households, and the one most likely to have extensive burner use. A CE of 0.55 is sufficient to maintain the indoor NO_2 below the 1-h threshold value in virtually all homes (>99%) larger than 1500 ft^2. Homes smaller than 1500 ft^2 would need higher burner emission capture efficiencies (0.70 to 0.75) to meet this threshold value.

Table 2. Percent of homes that exceed the NO_2 1-h threshold value for range hoods with the same capture efficiency but higher flow rates as drawn in Figure 1 for “two front burners”.

Burner Emission Capture Efficiency	Modeled Flow Rate (cfm)	% Homes Exceeding 100-ppb Maximum 1-hour					
		All Homes	Natural Gas Homes				
			All Gas Homes	<750 ft^2	750 - 1000 ft^2	1000 - 1500 ft^2	>1500 ft^2
0	0	49%	84%	100%	100%	100%	70%
0.50	160	19%	33%	95%	75%	47%	4%
0.55	180	14%	24%	85%	57%	30%	1%
0.60	200	9%	16%	66%	38%	16%	0.1%
0.65	225	5%	8%	42%	18%	3%	0%
0.70	250	1%	2%	18%	2%	0%	0%
0.75	280	0.09%	0.2%	1%	0%	0%	0%
0.80	310	0%	0%	0%	0%	0%	0%
0.85	350	0%	0%	0%	0%	0%	0%

We note that the simulations for NO_2 control used range hood airflows determined from testing with combustion burner pollutants from front burners (Figure 1a), and this testing found that higher airflows are needed to achieve a given CE compared to testing with the ASTM method (Figure 2). These higher airflows added substantially to the general ventilation when range hoods were simulated to operate in the smallest housing units, especially those smaller than1000 ft^2. We also note that the relationship used to model the CE vs. airflow relationship for combustion burner pollutants is through the middle of the available data. For example, in Figure 1a, a burner emission capture efficiency of 0.55 was measured for range hoods with airflows ranging from approximately 140 to 260 cfm. We picked a middle value, of 180 cfm, even though 180 cfm does not guarantee a burner emission capture efficiency of 0.55. We believe this is justified because some cooking will naturally occur on back burners, and users also have the option of using back burners preferentially for better performance, when air quality is a concern. As shown in Figure 1b, any cooking that is done on the back burner will have much higher CE for combustion pollutants. A meal that includes some front burner and some back burner cooking will have an overall CE better than the conservative, front-burner relationship used in the modeling for NO_2.

To enable flexibility in selecting a suitable range hood for a home of a given size, we note that the airflow determined in the above analysis can be translated to a CE value determined by the ASTM standard test for CE. This translation is uncertain because the ASTM test was not designed to measure performance specifically and only for pollutants generated by gas burners. As a conservative approach to provide equivalent protection, we used the curve shown in Figure 2 to find the ASTM CE that corresponds to each airflow highlighted in Table 2.

Using this approach and the fitted line shown in Figure 2, we determined that a range hood moving 180 cfm should have a corresponding ASTM CE of at least 0.70. Following this logic, homes that are between 1000 and 1500 ft^2 would need a range hood with a measured airflow rate of either 250 cfm or an ASTM CE of 0.80 to maintain 1-h NO_2 below the threshold value. For homes less than 1000 ft^2, either a measured range hood airflow rate of 280 cfm or an ASTM CE of 0.85 is needed.

Summary

Table 3 presents the ASTM capture efficiency or rated range hood airflows needed to avoid exceeding the World Health Organization 24-h $PM_{2.5}$ guideline level when cooking three meals in a day that all emit substantial quantities of particles or to avoid exceeding and NAAQS 1-h NO_2 threshold value when cooking a full meal with a gas cooktop and oven.

Table 3. Summary of ASTM capture efficiency or range hood airflows needed to meet 24-h $PM_{2.5}$ and 1-h NO_2 threshold value.

Threshold Value	Floor Area (ft^2)	ASTM Capture Efficiency	Airflow as installed (cfm)
24-h $PM_{2.5}$ 25 ug/m^3	>1500 ft^2	0.50	110
	1000 - 1500 ft^2	0.50	110
	750 - 1000 ft^2	0.55	130
	<750 ft^2	0.65	160
1-h NO_2 100 ppb	>1500 ft^2	0.70	180
	1000 - 1500 ft^2	0.80	250
	750 - 1000 ft^2	0.85	280
	<750 ft^2	0.85	280

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