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Measured pollutant removal performance of range-integrated downdraft exhaust kitchen ventilation devices

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SUMMARY

Cooking is one of the most substantial sources of indoor air pollution in most residences. This is mitigated most often by exhaust devices located near cooking surfaces. In this study, we measured the efficacy of one type of kitchen ventilation device which has been studied very little: a range-integrated downdraft ventilator. This was done via a full-scale mock-up of such a device. Results show that, to a greater degree than other kitchen ventilation devices, pollutant removal performance is highly dependent on location and type of source. Back-burner results for shallow emitters gave over 90% capture efficiency at a flow rate of 150cfm, while front-burner capture efficiency for taller emitters was below 30% even at the greatest flows tested (500cfm). Sensitivity tests were done to help inform a test method for such devices in the future.

KEYWORDS

Range hoods, kitchen ventilation, indoor air quality, cooking

1 INTRODUCTION

Many researchers have concluded that cooking is one of the most important sources of airborne pollutants in indoor environments. Cooking activities of all kinds, not just those done over an open flame, contribute additional pollutants, odors, and potentially undesirable levels of water vapor to indoor air (Fortmann, Kariher, & Clayton, 2001; Moschandreas & Relwani, 1989). The main mechanism by which the emissions of airborne pollutants described above is mitigated in homes is through the use of kitchen range hoods (Singer & Stratton, 2014). Many studies have looked at the efficacy of these hoods at removing emitted pollutants. It is near consensus that range hoods are indeed able to reduce concentrations of pollutants generated during cooking but the measured performance, even within individual studies, varies widely (Delp and Singer 2012; Lunden et al. 2014; D. H. Rim et al. 2011; Singer et al. 2011).

This investigation seeks to build on the lessons learned from previous works to better understand the operation of a subset of kitchen range hood devices which are becoming more popular: downdraft hoods that are integral with or immediately next to a range.

Specifically, we pursued two objectives in the course of this work:

1. Identify the performance parameters that have the greatest effect on the pollutant removal performance of these downdraft ventilation devices
2. Inform a method of test for downdraft devices to augment the recently published method for wall-mounted hoods (Standard Test Method for Measuring Capture Efficiency of Domestic Range Hoods, ASTM, 2017), here forward referred to as the ASTM Standard.

2 METHODS

Quantification of Capture Efficiency

Y. Li et al. (2001), Li and Delsante (1996), and Wolbrink and Sarnosky (1992) give slightly different versions of a similar means of estimating capture efficiency, which involve measurement of a tracer gas at multiple points and derivation of capture efficiency from these measurements. We chose to use the method of Wolbrink and Sarnosky (1992) which assumes no background ventilation and two well-mixed zones: one in which pollutants were emitted; and one which includes the rest of the room in question. Using conservation of mass, they showed that the fraction of emitted pollutants being exhausted by the hood can be estimated as:

$$\epsilon_c = 1 - \frac{c^r - c^o}{c^e - c^o} \tag{1}$$

Where ϵ_c is capture efficiency, or portion of pollutant captured by the exhaust; c^r is concentration of the tracer gas in a location representative of the room zone (ppm); c^o is concentration of the tracer in the make-up air (ppm); and c^e is concentration of tracer gas in the exhaust (ppm).

Overview of Chamber

A test chamber was built inside a laboratory building at the Lawrence Berkeley National Laboratory for the purposes of testing island and downdraft range hoods and developing a standardized test protocol that could be used to rate these devices. The chamber is a wood frame structure with gypsum board installed on interior faces and sealed except at dedicated makeup air vents as described below. Inside the chamber we used kitchen cabinetry to approximate a typical island that might be found in a residential kitchen. Integral to the island was a cooktop mock-up which consisted of a stainless steel surface assembled from several separate pieces that could be moved to adjust heating element/burner location. The burners are electric and fit snugly into machined holes in one of the stainless steel pieces.

The chamber was outfitted with makeup air vents to ensure measurements of flow rate through the range hood exhaust were accurate, makeup air interfered as little as possible with flow in the room, and all flow was induced by the fan in the range hood. 30 cm square makeup air vents covered with perforated plate diffusers were installed in each corner of the chamber at the ceiling. Preliminary measurements were made to ensure strong jets were not issuing from the diffusers. Maximum air velocities measured at the perforated diffuser were 0.4 m/s with a hood set at maximum flow, which quickly dissipated to 0.1 m/s less than 0.5 m from the diffuser. Vents were sealed with tape and the chamber pressurized to 50Pa to check leakage, which resulted in less than 2.5 air changes per hour of leakage.

The exhaust from the range hood exited the test chamber via a 15 cm diameter duct in the ceiling above the range hood. A 90-degree elbow connected this vertical duct to a horizontal duct containing a Brandt nozzle flow meter (ThermoBrandt Instruments NZP1031-10-1-CF) which was used for flow measurements. Connection to the Brandt nozzle was gasketed and bolted and ten centimeters of honeycomb material for flow straightening was provided upstream of the flow nozzle for additional flow conditioning. To control the air flow rate, an auxiliary fan and an iris damper were mounted two meters downstream of the flow nozzle. Inside the chamber, a bellowed heavy gauge flexible rubber coupler, was installed to allow for easy switching out of different hoods and a sealed connection. Sampling ports to measure the tracer gas concentration and air temperature ware installed upstream of the flow meter. All test chamber penetrations and duct connections were sealed with tape and mastic. Theatrical fog tests were performed inside the chamber to visually inspect for any leaks while the hoods were in operation.

Tracer Gas Distribution and Measurement

Carbon dioxide was used as a tracer gas in all experiments, owing to its lack of toxicity, ease of measurement, lack of legal and administrative hurdles, and cost. CO_2 was supplied through Norprene tubing from a cylinder in an adjacent room through a conduit installed in the floor of the chamber under the island, which also carried data communication wires. The CO_2 was heated with a 120V Titan Controls process heater at the cylinder to reduce the cooling effect of the CO_2 on the test apparatus and to prevent ice formation on the regulator. The flow rate of CO_2 was controlled by a 4-channel rotameter (Dwyer FT-754, +/- 1 lpm) installed between the supply tube and the tracer gas emitters, discussed below.

Two different emitters were used to supply the tracer gas into the plumes above the burners, as in previous work on development of a test method for wall-mounted range hoods (Walker, Stratton, Delp, & Sherman, 2016). The first emitter is a perforated copper tube coil with its end closed, submerged in a pot or pan of water on the burner. The second was engineered and machined specifically for the purposes of these tests and is described in the ASTM Standard.

Tracer gas was measured in three locations, similar to the locations specified in the ASTM Standard (Exhaust, Breathing Zone, Ambient) with two small differences: First, ambient (inlet) concentration was established by sampling from four equal-length Norprene tubes, each running from one makeup air vent to a central hub above the chamber. This effectively averaged the slightly different CO_2 concentrations between locations. Second, instead of modifying the sampling height for the breathing zone sampler with changes in range hood height, as is specified in the ASTM Standard, all breathing zone samples were taken at a height of 130 cm above the ground, which corresponds to half the vertical distance between a typical counter surface and the face of a range hood 76 cm above the counter, which was deemed a typical installation height after consultation with manufacturers and installers. All measurements were taken 50 cm horizontally and perpendicularly from the front face of the "range" as is specified in the ASTM Standard.

Tracer gas concentrations were measured with PP Systems EGM-4 CO_2 analyzers with precision of 1 part per million, which were tested and/or calibrated bi-weekly with calibration gas. Maximum absolute error after calibration was around 2 ppm. Capture efficiency was calculated using these concentrations with Equation 1 and averaged over a fifteen minute period, or approximately 45 samples. If we assume conservatively that the errors in each concentration measurement used to derive capture efficiency are additive, this translates to around 0.2% error in capture efficiency due to precision and accuracy. In contrast, the standard deviation of the approximately 45 capture efficiencies measured over a fifteen minute averaging period ranged from around 3% to 10% due to fluctuations in concentration with time caused by turbulent flow in the chamber. Combination of the two errors shows the precision and accuracy errors are less than the least significant digit in the capture efficiency even with conservative assumptions. For this reason, reported error is only temporal error, the standard deviation of the 45 or so instantaneous capture efficiency values averaged for each experiment.

Power Measurements

Power consumption of the electric burners was measured using Wattnode WNB-3Y-208P meters with an accuracy of 4% of the reading. Manufacturer calibration curves were applied to the Wattnode signals to translate them to power consumption. Instantaneous power measurements were recorded approximately every 20 seconds, and these measurements were averaged over the same averaging period as the tracer gas concentrations for analysis purposes.

Burners

Cadco-CSR-3T hot plate heating elements were used as the heat source/burner. Note that the power supplied to the heating elements was conrtolled with variable transformers rather than their own internal controls because their built-in control resulted in on/off cycling. By running them at the highest setting, and controlling power input with the variable transformer they only cycled off for 6% of the time, which had a negligible effect on the temperature of the emitters, owing to the thermal mass of the emitters. The removable stainless steel panels were designed to allow the burners to be moved up to 300mm from the centerline of the exhaust range hood (coincident with the centerline of the island). Along the axis of the island, burner location was fixed as dictated by the housing at 300mm from the centerline of the range hood.

Temperature Measurements

Temperature measurements were made at multiple locations throughout the chamber for the purposes of verifying a steady state condition had been reached and investigating any anomalies which might appear in the data. Surface temperatures on the burner surface were measured with Type K thermocouples attached with high-temperature tape. Air temperatures were measured with calibrated thermistors. Thermistors were placed directly above and below the "breathing zone" tracer gas sampling tube at 50 cm vertical intervals to measure stratification in the room. Thermistors were also placed at each of the makeup air vents and in the exhaust. All temperature data was sent to a LabJack L7 data acquisition system. Real-time temperature data were used to ascertain a steady-state condition only.

Achievement of Steady State Conditions

All reported values of capture efficiency are steady-state values unless otherwise noted. As was done in Walker et al. 2016, we looked at both individual measurements of concentration and derived capture efficiency to determine achievement of a steady state condition. Perhaps more important in our investigations than in those done for wall-mounted hoods, we also measured temperature of the emitter surface and range surface in two places, and air temperature in five places to help in determining if steady-state conditions had been reached. Temperature measurements were very stable and it was possible in all experiments to achieve a condition where temperature did not change more than 0.2K over a fifteen-minute averaging period. The uncertainty in the reported values is then given, as is done in all cases, as the standard deviation of this set of measured values, which represents the temporal error only over a fifteen minute or more averaging period as explained above.

Testing Procedure

Two to four hours were needed until the experiments came into near-thermal equilibrium. After the room reached near-thermal equilibrium, CO_2 injection began, and another one half to two hours were required for the concentration field in the space to reach steady state- depending on the exhaust flow rate of the hood. After this, other exhaust flow rates could be tested and 0.5 to 1.5 hours was required for the concentration field to again reach steady state.

3 RESULTS

Initial Investigation of Emitter Types

One downdraft exhaust hood (Broan DD0136SS) was tested with three different tracer gas emitters to understand the effect emitter design on measured performance: the ASTM-E3087-17 engineered emitter, a pot with water and tracer gas injected into the water, and a shallow pan also with water and tracer gas injected into the water. All tests were done at 920 W to ensure boiling of the water.

Two general trends are evident in the results of these tests shown in Figure 1. First, there are discrepancies as great as 35% in capture efficiency for the same input power and exhaust flow rate depending on the emitter. This is almost certainly due to the fact that the tall pot extended beyond the zone of influence of the downdraft hood. Secondly, the performance of the hood with any emitter on the front burner was very poor relative to other values reported in the literature at similar flow rates.

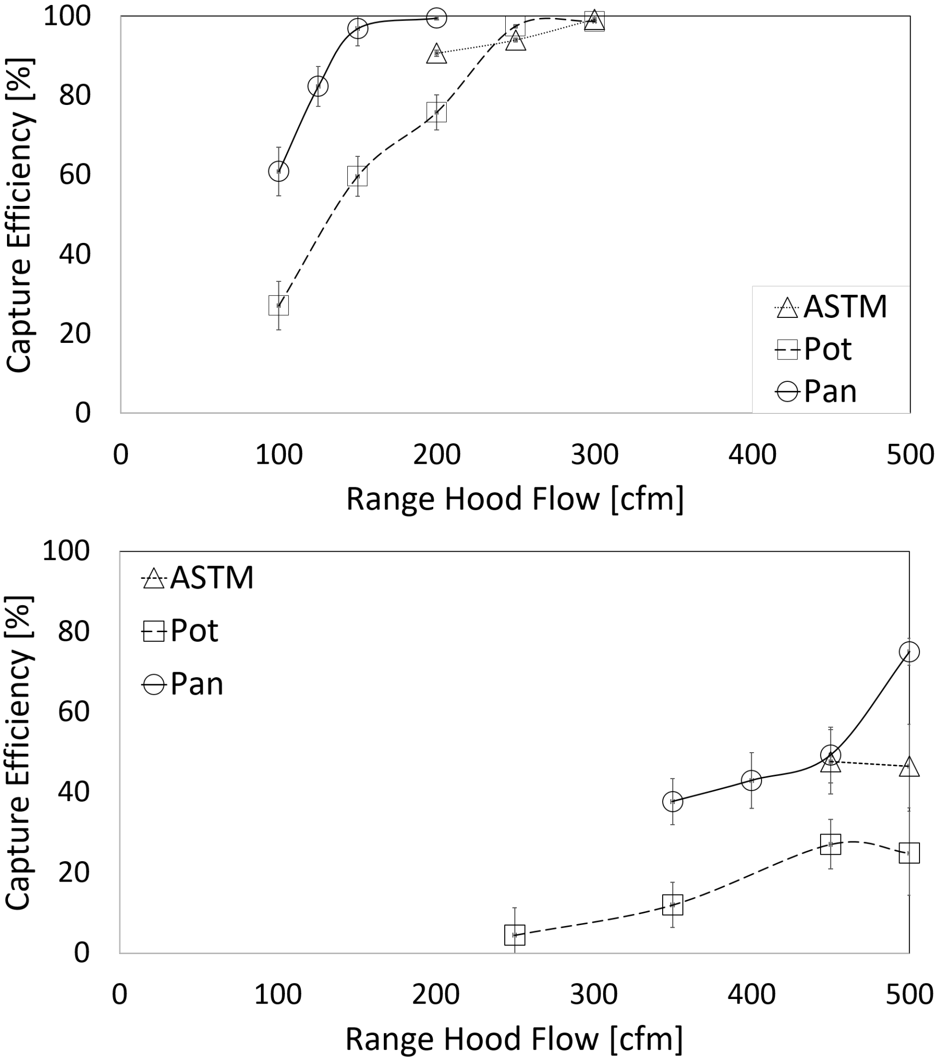

Figure 1. Capture efficiency results with different emitters on back burner (top) and front burner(bottom)

Effect of power variation and burner location on measured performance

We tested the downdraft hood with burners operating at several different power settings. All experiments in this phase were conducted with the ASTM emitter for consistency and ease of comparison. Again, two general trends can be taken from the results presented in Figure 2. At medium-high power, the downdraft performed poorly when used to extract tracer gas emitted from the front burner for all but possibly the highest flow setting, even with emitters whose height was much less than the height of the downdraft hood. In contrast, the hood performed very well for the back burners even at lower flow rates. There was little to distinguish back-burner experiments with regard to burner power input or flow rate, suggesting this is not a location for rating experiments. When the burner was placed in the center of the range, performance varied strongly with flow rate.

Large uncertainty existed in the front burner experiments at high power. This is likely due to the fact that fluid mechanics in the plume in these experiments were driven to a much greater degree by the natural convective flows generated by the burner heating below the plume rather than the forced air movement of the hood.

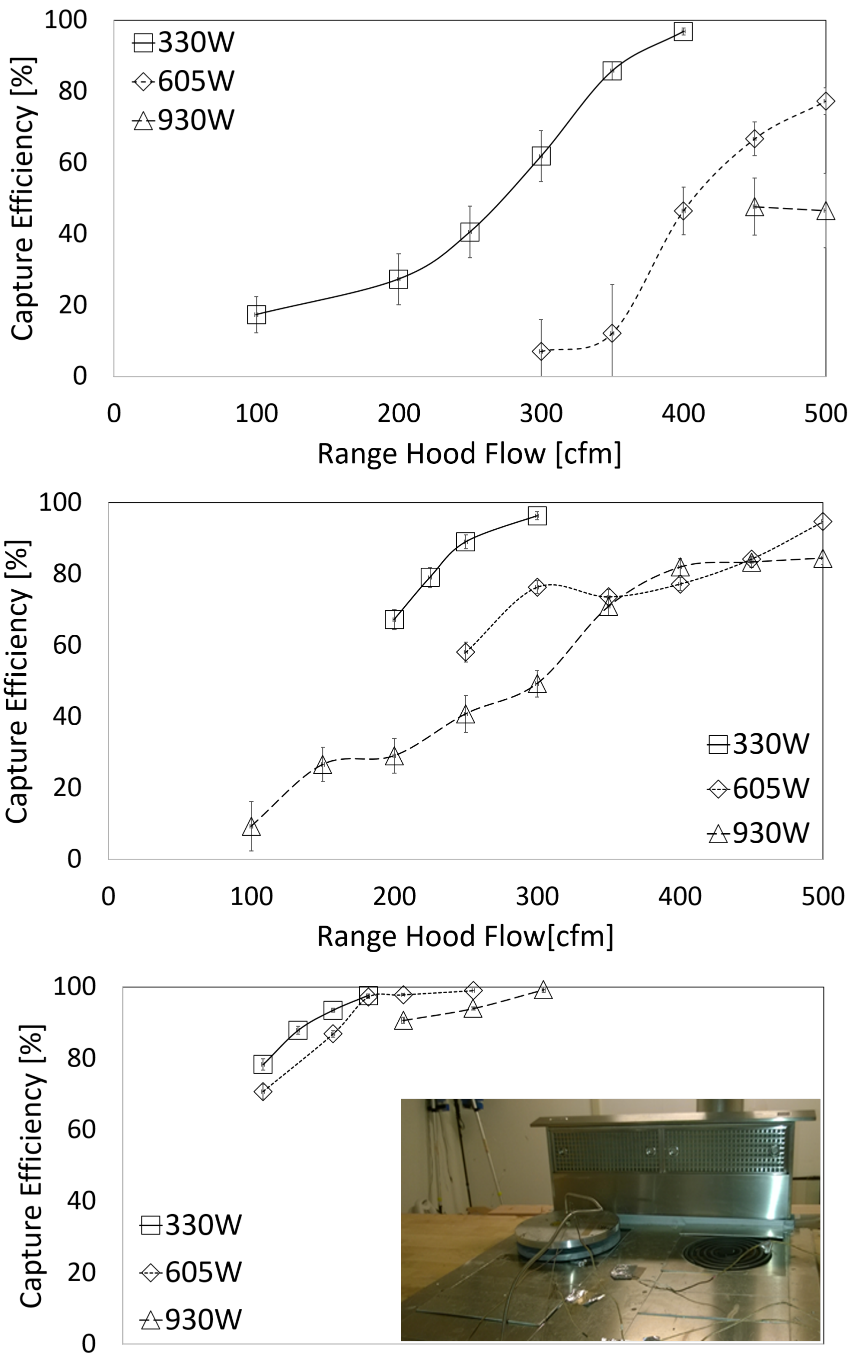

Figure 2. Effect of variation of power input on front (top graph), center (center graph) and back (bottom graph) burners

Two Burners

Tests were also performed to measure the effect of simultaneously operating a front and back burner. All tests were done at the intermediate power value of 605W. Results are presented below in Figure 3. At lower flow rates, the capture efficiency nearly approximated the performance of the hood when a single burner was placed at the center of the range. However, at higher flow rates, the measured performance of the hood with two burners operating was lower than any single burner. This suggests some interaction of the two plumes to the detriment of burner performance.

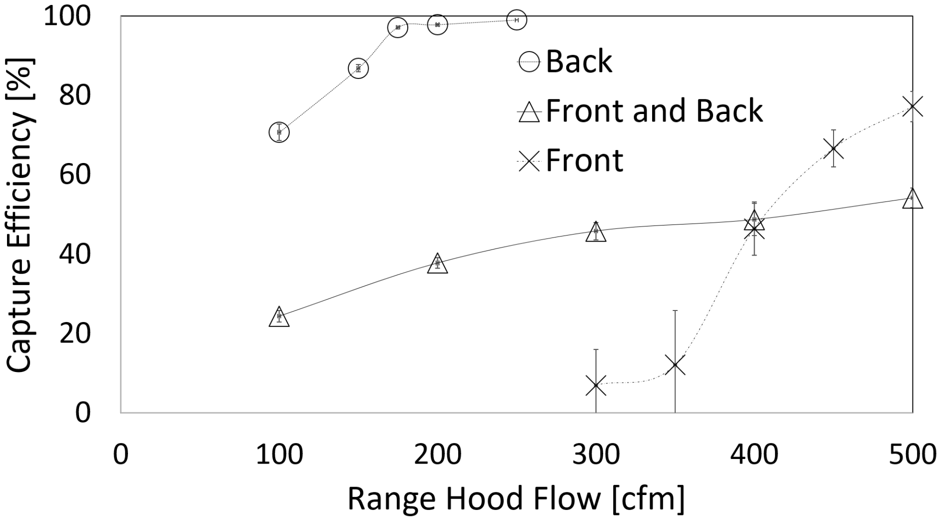

Figure 3. Effect of simultaneously emitting from two burners

4 DISCUSSION

For downdraft hoods, the use of the ASTM emitter is not necessarily conservative. The ASTM emitter gave higher capture efficiency values than a pot of boiling water with tracer gas injected in the water. However, specifying a pot of water, the amount of water, and the procedure for measuring this type of emitter presents other practical challenges. We leave it to standards development teams to decide which of these concerns is more important.

The choice of burner location had a drastic effect on measured capture efficiency. For example, at 350W input power, an emitter on the front burner resulted in nearly 80% worse capture efficiency than one on the back burner. We recommend that in order to be conservative and be able to compare with other types of exhausts, emitters be placed at least on the centerline of the range, if not farther from the hood. Unlike for overhead island exhausts (Clark et al. in publication process), in the case of downdraft hoods, 2-burner results were worse than any of the 1-burner tests except at the highest flow rate.

The testing done as part of these investigations showed, as others have, that for the same range hood flow rate and height, very different capture efficiency is measured with different power inputs to burners. For downdraft hoods, discrepancies as great as 55% in measured capture efficiency existed at the same flow rate for only a 275W difference in power input. One can easily imagine this making the difference between a “passing” range hood and a “failing” one in any future standard that may be developed. It is important to state the obvious here: that the input power is not a function of the range hood being tested, yet it plays a large role in the determination of its apparent efficacy.

5 CONCLUSIONS

The test results show that any future testing standard will need to pay close attention to the burner location and power input under which tests are performed. Values of capture efficiency given in this report provide some understanding of the performance of downdraft devices, suggesting rear burner cooking is very much preferable to front burner cooking from an indoor air quality perspective. Testing of additional downdraft range hoods is needed to assess the generality of the results presented here.

ACKNOWLEDGEMENT

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