Title

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Towards the development of a standardized testing protocol for overhead island kitchen exhaust devices: procedures, measurements and paths forward

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Disclaimer

1. INTRODUCTION

Cooking is one of the most important sources of airborne pollutants in the indoor environments of residential buildings. Elevated concentrations of NO_2 due to cooking have been reported widely (Garret et al. 1998; Garrett et al. 1999; Mullen et al. 2016; Ryan et al. 1988; Schwab et al. 1994; J. Spengler et al. 1994; J. D. Spengler et al. 1983; Wilson et al. 1995). Many researchers have attributed elevated particulate concentrations to cooking, and some have attributed extremely high short-term concentrations of fine particles (>300 $\mu g/m^3$) and ultrafine particles (>105 $\mu g/m^3$) to cooking events (Abdullahi et al. 2013; Abt et al. 2000; Afshari et al. 2005; Buonanno et al. 2009; He et al. 2004; Kearney et al. 2011; Lance A. Wallace et al. 2004; See and Balasubramanian 2008; Stieb et al. 2008; Wallace and Ott 2011; Wheeler et al. 2011; Zhang et al. 2010). Cooking is also a source of other gas-phase pollutants including carbon monoxide, formaldehyde, acrolein, and other volatile organic compounds (Garret et al. 1998; Garrett et al. 1999; Logue et al. 2013; Mullen et al. 2016; Ryan et al. 1988; Schwab et al. 1994; J. Spengler et al. 1994; J. D. Spengler et al. 1983; V. Seaman et al. 2007; Wilson et al. 1995). Lastly, cooking can be a significant source of water vapor, and the water vapor produced from cooking can eventually lead to moisture-related problems (Parrott and Emmel 2003)

The main mechanism by which the source of these airborne pollutants is reduced is via kitchen range hoods. Many studies have looked at the ability of these hoods to reduce concentrations of pollutants generated during cooking, and it is generally believed that they are indeed effective (Chiang et al. 2000; Fugler 1989; J. M. Huang et al. 2004; Y. Huang et al. 2015; Mullen et al. 2016; Revzan 1986; D. Rim et al. 2012; B. C. Singer et al. 2012c; Singer et al. 2011; Svendsen et al. 2002; Zhang et al. 2010). However, even within individual studies the measured performance has varied widely (Delp and Singer 2012; Lunden et al. 2014; D. H. Rim et al. 2011; Singer et al. 2011). The variation in performance is at least partially attributable to differences in installation, burner position, fan speed, fan design, hood design, and location of makeup air (Fritz 1989; Singer et al. 2010; Singer et al. 2011) and particle size when quantifying particulate removal (D. Rim et al. 2012). Measured performance has varied up to almost 100% even within a given study (Li et al. 1997; Li and Delsante 1996; Lim and Lee 2008; Madsen et al. 1994; D. Rim et al. 2012; Singer et al. 2011).

Furthermore, the lack of a standardized method of testing and rating such devices has led to some confusion, lack of clear guidance for consumers and standardizing bodies, and even counterproductive measures-such as manufacturers creating range hoods that move ever-more air in order to maintain a competitive edge in the market. For now, governing bodies give recommendations almost solely in terms of minimum airflow rates and noise. For example, ASHRAE Standard 62.2 (ASHRAE 2016) specifies minimum flow rates of 100 cfm (50 L/s) and a maximum sound level of 3 sones. While many researchers have shown a correlation between range hood flow rate and pollutant capture (e.g., Singer et al. 2010), flow rate is not the sole determinant of the capture efficiency of range hoods and is not suitable as a stand-alone indicator of performance. Researchers have shown as much as a factor of three variation in hood performance at the same flow rate (Delp and Singer 2012; Singer et al. 2012a). Other variables independent of flow rate may also contribute strongly to hood performance, such as the power input into the range (Yuguo Li and Delsante 1996), emitter temperature (Walker et al. 2016), face velocity (Kuehn et al. 1989), and emitter height (Kuehn et al. 1989). Furthermore, one study found that for one particular hood, the increase in performance with flow rate fell off markedly above 250 cfm (118 L/s) (Delp and Singer 2012; Singer et al. 2011).

To complicate matters further, actual flow rates of range hoods are rarely commissioned in homes. Flow rates used as indicators of hood performance in practice are almost always *rated* flow rates. Singer et al. (2011) showed that the rated flow rate is often not achieved in real homes, and that 10 devices they tested had maximum airflows 70% or more below rated values. In tight, energy-efficient homes, fans may be working against restricted make up air flow and therefore be substantially less effective (Fritz 1989). High-resistance exhaust ducts with no auxiliary fan included can make the rated flow rate nearly meaningless (Brett C. Singer and Stratton 2014).

For these reasons, a recent report from Lawrence Berkeley National Laboratory identified the development of a testing method for kitchen range hoods as a “specific high-priority near-term objective” (Brett C. Singer and Stratton 2014). This test method would move the quantification of kitchen range hood performance from solely a rated flow rate to a metric that more fully captured the ability of the hood to improve air quality. This was followed by the development of such a method for wall-mounted hoods (Walker et al. 2016).

2. Scope and Objectives

This investigation seeks to build on lessons learned from these previous works and others in order to better understand the operation of a subset of kitchen range hood devices that are becoming more popular- overhead island exhaust hoods- and help inform a standardized test method for these devices. A new facility was built at Lawrence Berkeley National Laboratory to aid in developing a test method for these devices. The scope of this investigation includes only the laboratory performance of one island device and the variables affecting capture efficiency. It is the first study, to our knowledge, looking at performance of island hoods, and thus is preliminary and exploratory in nature. Heavy emphasis is placed on experimental method and quantification of uncertainty, as it is the motivation for this work. It does not include installed performance in the field, nor the performance of wall-mounted devices, nor a comprehensive market survey. It also does not include assessments of noise performance, or pollutant removal performance of recirculating range hoods.

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

- Construct a test facility which can be used to measure the efficacy of overhead island kitchen exhaust hoods
- Identify the variables which have the greatest effect on the pollutant removal for these devices and attempt to understand their effects
- Recommend any necessary facets of a method of test for island exhaust hoods

3. Methods

3.1 Quantification of Capture Efficiency

In the Introduction, we discussed the disadvantages of the most commonly used range hood performance metric: rated flow rate of the range hood fan. Other methods for assessing performance include direct visualization of flow fields (popular for commercial devices), such as those specified in ASTM F1704-12, UL 710, and IMC.507.16.1, and Kuehn et al. (1989). Alternatively, Rim et al. (2011) defined a method for quantifying the capture of particulate matter by kitchen range hoods, and Singer et al. (2011) used the stoichiometry of the combustion reaction along with metered gas data and exhaust CO_2 measurement to derive capture efficiency.

Possibly the most widely used method in residential applications is the injection of a tracer gas directly into the plume and the measurement of the gas at representative locations in order to derive the capture efficiency. Y. Li et al. (2001), Li and Delsante (1996), and Wolbrink and Sarnosky (1992) have given slightly different versions of a similar means of estimating capture efficiency which involves measurement of a tracer gas at multiple points and derivation of capture efficiency from these measurements. Li et al. (1997) furthered clarified this work. Other methods such as Schlieren photography might be more appropriate for some applications, but we adopt the tracer gas method for this work and thus explain it in more detail presently.

Wolbrink and Sarnosky (1992) started with the assumption of two well-mixed zones: one that encompasses the range and range hood in which the pollutants are emitted; and one that includes the rest of the room in question. Using conservation of mass, they showed that the fraction of pollutants being exhausted by the hood relative to the total emission can be estimated as:

$$\boldsymbol{\epsilon_c = 1 - \frac{c^r - c^o}{c^e - c^o}} \qquad \text{Equation 1}$$

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

Li and Delsante (1996) argued that conceptual inconsistencies in Wolbrink and Sarnosky's (1992) formulation necessitated inclusion of a general ventilation term. The resulting equation included three concentrations that needed to be measured as well as two distinct flow rates, and reduced to the Wolbrink and Sarnosky equation when the background ventilation term was zero. Li et al. (2001) suggested anothevr formulation that not only accounted for a background ventilation process, but also attempted to account for any gradients in tracer concentration within the room that might exist. In order to do this, they suggested defining an "entrainment boundary" at which the plume from the range ended and the relatively quiescent room air began, measuring the concentration along this boundary, and then averaging these concentrations to get a slightly more accurate estimate of capture efficiency. This method lends itself more readily to numerical analyses (such as CFD) because it requires the concentration to be known at many points. For this reason it was not used.

For our purposes, we did all experiments at steady state in a closed environmental chamber and we sought to develop a method that was not overly onerous for manufacturers to replicate. For these reasons, we opted to use the Wolbrink and Sarnosky (1992) approach and assume the background ventilation term suggested by Li and Delsante (1996) was zero and a single breathing zone sample was representative of the room.

3.2 Chamber

A new 15' x 15' x 8' (4.6 m x 4.6 m x 2.4 m) testing chamber was built at the Lawrence Berkeley National Laboratory for the purposes of testing island and downdraft range hoods and developing a test protocol for doing so. The chamber is a wood frame structure with gypsum board installed on interior faces and sealed except where dedicated makeup air vents were located as described below. Inside the chamber we constructed an island that approximated a typical island that might be found in a residential kitchen.

Integral to the island was a "range" mock-up. We performed a brief market survey of available island ranges prior to selection of a burner with the goal of defining a typical island range. However, it quickly became apparent that no such typical configuration exists; cooktop and range designs vary widely. For this reason, we decided to mock up a "range" out of individual burners which could be moved and the effect of burner location on range hood efficacy assessed. An aluminum template was machined with modular pieces which formed a cover for burners placed underneath within the island as shown in Figure 1. The location of the pockets for the burners was dictated exclusively by the housing of the burners themselves and their ability to fit into the range mockup. We cut the removable panels such that the burners could be moved up to 12 in (30 cm) 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 12 in (300 cm) from the centerline of the range hood. The burners fit snugly into machined holes in such an aluminum piece that could also be moved and switched with the rectangular pieces, as shown below in Figure 1.

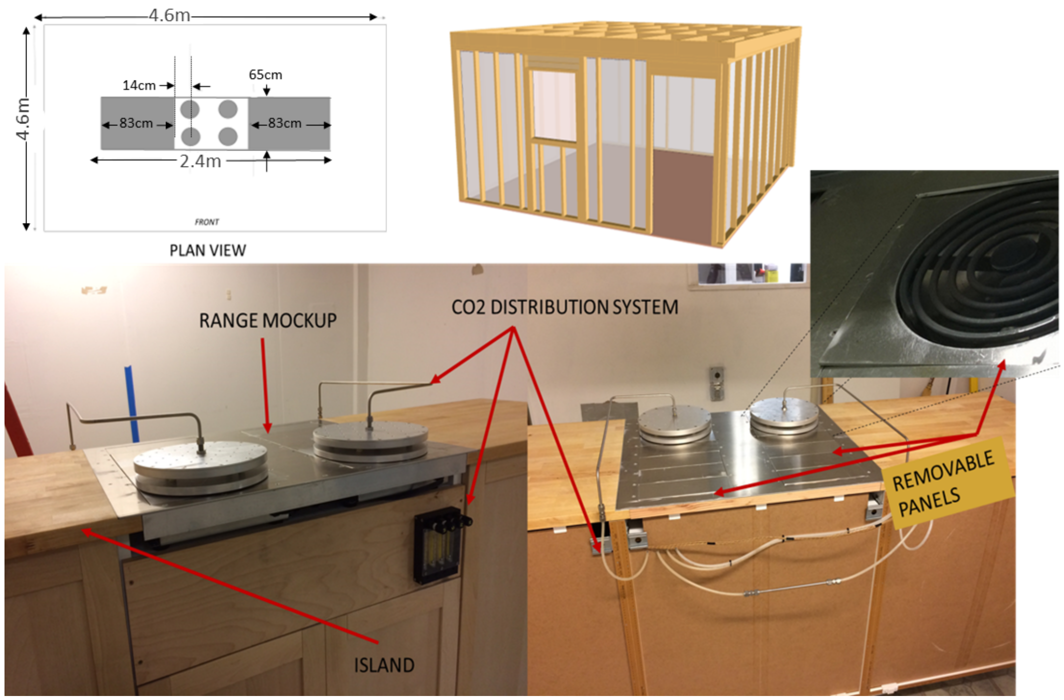

Figure 1. Photograph of range mock-up and plan dimensions of chamber and range.

3.3 Burners

We selected the burners themselves based on the following experimental requirements: They needed to be of good quality to ensure durability and robust repeatable results; they needed to be capable of supplying sufficient power to achieve the conditions we wished to test; and they needed to be widely available for a reasonable price. The latter consideration is because we want other laboratories to be able to perform the same testing in a standardized way using the same or very similar test apparatus. Additionally, burners needed to be relatively simple in their control, in order for us to have control over burner operation. After eliminating a similar model with a cast iron solid heating element which failed to deliver the temperatures we wanted to test, we decided that the Cadco-CSR-3T was the burner most suited to the needs of the experiments. The burners were mounted in stainless steel housing 14 inches (36 cm) by 12 ¼ in (31.1 cm) in plan and 4-1/8 (10.5 cm) tall with 8 inch (20 cm) diameter heating elements.

Surface temperatures on the burner surface and "range" surface were measured with Type K thermocouples (±1.5 °C accuracy up to 400 °C) attached with high-temperature tape and recorded. Air temperatures in the space were measured with calibrated thermistors (±0.2 °C accuracy from 0°C to 100°C). Power was measured using Wattnode WNB-3Y-208P meters (accuracy of ±0.5% of reading at 1-15 amps and 90-125 V). Manufacturer calibration curves were applied to the Wattnode signals via a Python script to translate them to power. This power was verified with a plug-through power meter at the beginning of the measurement campaign.

3.4 Power control

The burner model we selected and similar ones supplied around 1300 W at their highest setting. We soon found that this power was sufficient to melt the aluminum emitter plates. Air temperatures immediately under the emitter exceeded 600 ^oC (1112 ^oF) at 1300 W. We then modified power control to ensure melting didn't occur. Burners were set at their highest setting and power was controlled by a variable AC-AC transformer between the WattNodes and the burners. This limited the output to 1100 W or less, which prevented melting of the emitter plate. Temperatures near the burner surface in this case were less than 550 ^oC (1022 ^oF).

The burners used in these experiments had internal mechanical controls that cycled off power supplied to the heating elements 6% of the time at the highest burner setting. We did not disable this control for safety reasons. Instantaneous power measurements were taken approximately every 20 seconds, and these measurements were averaged over a period of at least fifteen minutes to give the reported value (the same 15-minute sample period as for the tracer gas sampling). This fifteen minute average power deviated less than 1% from its 30-minute average. The cycling had a negligible effect on the temperature of the emitters they were heating, owing to the mass of the emitters. The standard deviation of the emitter temperature during a typical fifteen minute period was 1 ^oC (2 ^oF), less than 1% of the average temperature. For this reason we assumed that treating the power supply as constant, at the average of the values recorded, was appropriate.

3.5 Ventilation and Flow Measurements

We installed one-foot (30 cm) square makeup air vents covered with perforated plate diffusers at the corners of the chamber at the ceiling as shown in Figure 2 to ensure that makeup air interfered as little as possible with the flow patterns in the room and that all flow was induced by the operation of the hood only. Maximum air velocities measured at the perforated diffuser were 80 fpm (0.4 m/s) when an overhead island hood was set at maximum flow, which quickly dissipated to 20 fpm (0.1 m/s) at less than 1.6 ft (0.5 m) from the diffuser. At the start of the project, we sealed the vents and pressurized the chamber to 50 Pa to check leakage, which resulted in less than 2.5 air changes per hour of leakage, which translates to less than 1 cfm (0.5 L/s) under typical experimental pressures.

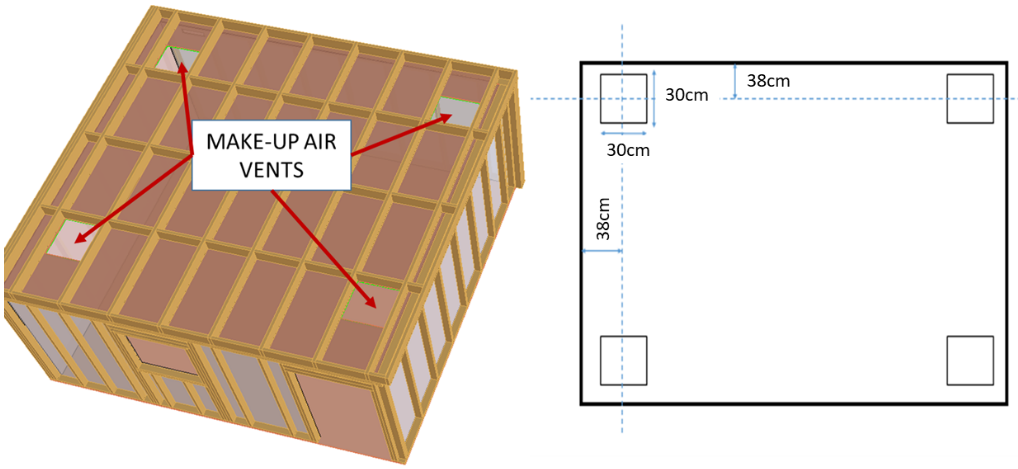

Figure 2. Rendering and plan drawing showing locations and sizes of makeup air vents

We cut a hole in the center of the ceiling and placed a six-inch (15 cm) duct through the hole, then sealed the hole with spray foam insulation. We then installed a 90-degree elbow between the vertical duct and a Brandt nozzle flow meter (ThermoBrandt Instruments NZP1031-10-1-CF, accuracy of ±0.5% of reading down to 1/34 of nominal maximum reading of 30 m/s maximum velocity). Connection to the Brandt nozzle was gasketed and bolted. We provided ten centimeters of honeycomb material for flow straightening upstream of the nozzle and six feet (2 m) of straight duct downstream of the nozzle. Lastly, we installed an Iris damper upstream of the exhaust fan to allow for precise (<3 cfm or 1.5 L/s) changes in flow rate.

We tested one overhead island range hood (Broan EI5936SS) in the course of this work. The glass canopy has nominal dimensions 35-3/8" X 25-5/8" (90 cm X 65 cm) and the hood can be mounted at distances from 24” to 36” (61 cm to 91 cm) from the hood face to the range surface. The installed hood is shown below in Figure 3. It was installed according to manufacturer recommendations and all ducting between the measurement locations was thoroughly sealed. Theatrical smoke tests were performed to visually inspect for any leaks while the hoods were in operation.

Figure 3. Overhead island range hood tested

3.6 Tracer Gas

We used carbon dioxide as a tracer gas in all experiments, owing to its lack of toxicity, ease of measurement, lack of legal and administrative hurdles, and low cost. We supplied CO_2 through Norprene tubing from a cylinder in an adjacent room, under the testing chamber, into the range mockup to minimize opportunity for leakage into the space. Directly out of the cylinder, CO_2 was heated with a 120V, 1 amp Titan Controls process heater. CO_2 was heated to approximately 79 °C according to the manufacturer, although this was not measured. It was then routed through an un-insulated Norprene tube approximately 10 m long before being delivered to the emitters. Flow rate of CO_2 was controlled by a 4-channel rotameter (Dwyer VA 10412, ±2% full scale (2.5L/min) accuracy) installed between the supply tube and the tracer gas emitters, discussed below, and monitored with a mass flow meter. The rotameter and the emitters are shown above in Figure 1.

We used two different emitters to supply the tracer gas into the plumes created by the range mockup. This is in following with previous work (Walker et al. 2016) in the development of a test method for wall-mounted range hoods. The first emitter is a spiral perforated copper tube coil with its end closed. In the cases referred to as “inject inside pot [or pan]” in this report, we submerged the coil in water in a pot [or pan], and in those labeled “inject under pot” we wrapped the coil around the heating coil of the burners, in order to inject under the pot. The second is a custom machined aluminum emitter identical to that described in newly published Standard Test Method for Measuring Capture

Efficiency of Domestic Range Hoods (ASTM International 2017), here forward referred to as the ASTM Emitter.

Tracer gas was measured in three locations, identical to the locations specified in ASTM-E3087-17 (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 slight differences in CO_2 concentration that existed between the four inlet locations. Second, instead of modifying the sampling height for the breathing zone sampler with changes in range hood height, as is specified in ASTM-E3087-17, all breathing zone samples were taken at a height of 51 in (130 cm) above the ground, which corresponds to half the vertical distance between a typical counter surface and the face of a range hood installed 30 inches (76 cm) above the counter-deemed a typical installation height after consultation with manufacturers and installers. This was done in order to be able to attempt to generalize results by eliminating sampling height as a variable. All measurements were taken 20 in (50 cm) horizontally and perpendicularly from the front face of the “range” as is specified in ASTM-E3087-17. Tracer gas concentrations were measured with PP Systems EGM-4 CO_2 analyzers with a resolution of 1 part per million, which were tested and/or calibrated bi-weekly with calibration gas of known concentration. Maximum absolute deviation from manufacturer’s analysis of calibration gas after calibration was around 2 ppm.

3.7 Achievement of Steady State Conditions

All reported values of capture efficiency in this report 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 locations, and air temperature in five locations and used this data to determine a steady state condition 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 0.2 °C (0.4 °F) over a fifteen-minute averaging period.

The same was not necessarily true for concentration measurements. As in Walker et al. 2016, we attempted to perform all experiments such that a reading was not considered valid until less than a 5% change in capture efficiency was recorded over the averaging period. However, at lower flow rates (below 200 cfm or 94 L/s) this was not always possible, likely because of some combination of four differences in setup:

1) The much larger volume of the test chamber used in this investigation,
2) The lower air exchange rates tested (owing mainly to the larger room volume),
3) The type of hood tested (overhead island hoods are often marketed as 500 cfm (240 L/s) or greater hoods, whereas wall-mounted hoods are expected to be operated closer to 200-300 cfm (94 -140 L/s)). This is reflected in the recommended flow rates for these devices, which are 50% higher for island ranges (ANSI/ASHRAE 2016; HVI 2008)
4) In some cases the lesser power supplied to the burners.

Below in Figure 4 is an example of the “steady state” condition that was reached when an overhead island range was operated at 150 cfm (71 L/s). This type of behavior was quite common at hood flow rates below 200 cfm (94 L/s) and is reflected in the large uncertainty for measurements in this range given in the results section of this report. A stably periodic flow condition has developed which results in a stably periodic reading of exhaust concentration, with a period of approximately three minutes (periods from 1-5 minutes were observed in different experiments). Periodicity was present in some measurements of room concentrations as well. In cases such as these, which occurred exclusively at flow rates below 200 cfm (94 L/s), a “steady state” value of capture efficiency is reported which is the average of at least three such periods in the oscillating capture efficiency. In other cases at low flow rates, no periodicity was obvious, but the standard deviation in the concentration over fifteen minutes was nearly 50% of the mean value.

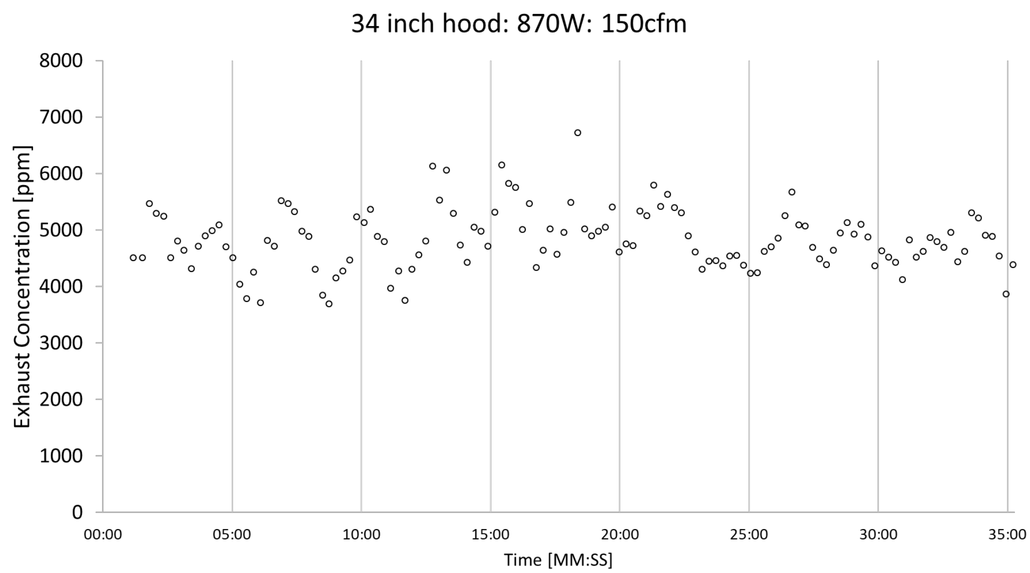

Figure 4. Example of periodicity in exhaust concentration measurement.

An example of a “good” data point (lacking periodic behavior) is given in Figure 5. Figure 5 was generated from an experiment run at 400 cfm (190 L/s). From Figure 5, we can see that once the concentration field reaches stead state, which as in Walker et al. (2016) takes around four air changes (18 minutes at this flow rate), the standard deviation in the previous twenty measurements drops below one percent in capture efficiency. This suggests a possible metric for defining what constitutes a valid data point. This threshold could be increased to 2% and still preclude the highly unstable readings at low flow rates, which usually had standard errors of 5-10%. For these reasons, we do not present data measured at flow rates less than 200 cfm (94 L/s) except for a few instances in which it is necessary. Ultimately, we recommend future testing either be performed above a certain flow rate threshold to avoid this source of uncertainty, or that a maximum standard error, say 2%, be required in any method of test to ensure a valid reading.

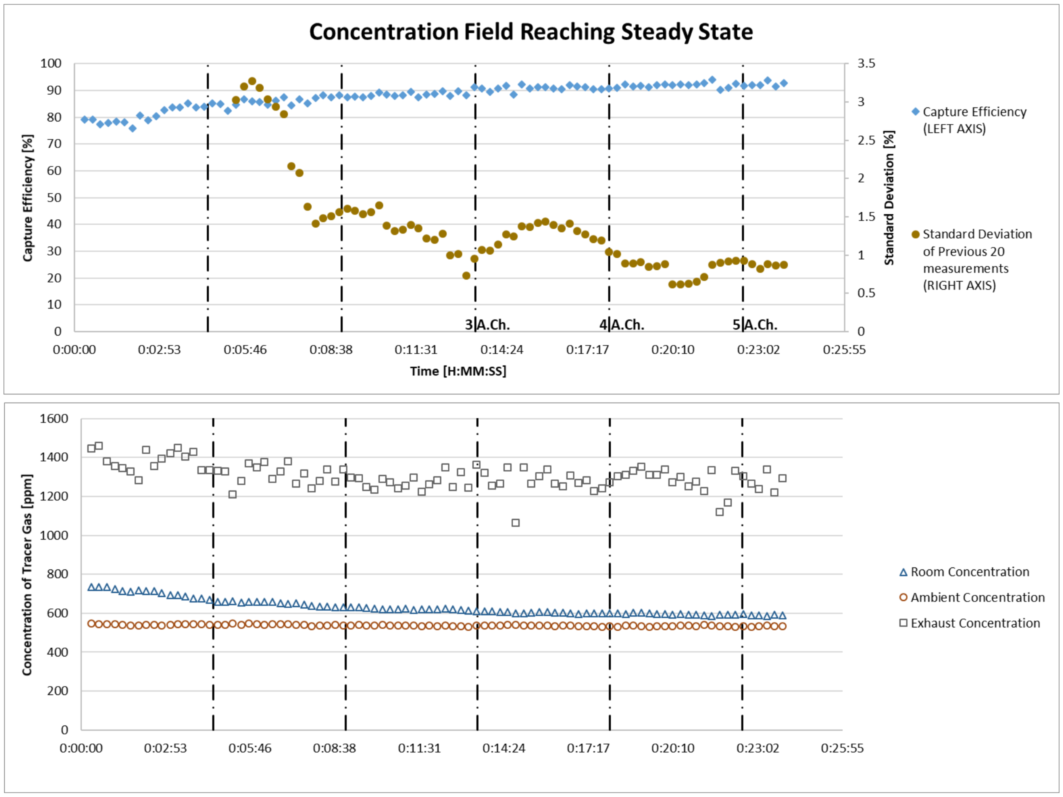

Figure 5. Example of concentration field reaching steady state

3.4 Error Analysis

We attempted to minimize error throughout our investigation and report uncertainty in a meaningful way. Walker et al. (2016) previously did extensive testing to minimize systematic errors such as those arising from the location of the sampling tubes and the calculation of capture efficiency, and we follow their recommendations in this work.

The greatest remaining source of uncertainty in reported measurements, by far, was temporal error. If we assume conservatively that the measurement 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. However, quantification of temporal error is not straightforward as each capture efficiency reported is a function of three individual concentrations, each of which is varying in time. Two distinct approaches to quantifying temporal error exist:

- **Averaged**-Since capture efficiency is a derived quantity and a function of three measured variables, uncertainty in capture efficiency could be quantified by first averaging each concentration over fifteen minutes and calculating temporal uncertainty in each concentration, and then propagating each of these three uncertainties into the derived capture efficiency (see Equation 1 above). However, this effectively assumes that each concentration is independent and that uncertainties in each are additive. This is not the case because the mass balance ensures the concentrations are highly correlated. For this reason, this method may overestimate uncertainty in capture efficiency.

- **Instantaneous**- Alternatively, instantaneous derivations of capture efficiency, calculated in real time from coincident instantaneous concentration values with the Python script used for data acquisition, could be used. Uncertainty in capture efficiency is then calculated as the standard deviation of the 45 or so instantaneous capture efficiencies calculated over the averaging period. We believe this more accurately reflects the uncertainty in the measurements.

Below, a sample measurement is used as an illustrative example. Uncertainty is calculated using the two methods outlined above. In this example, errors quantified in the two different manners differ by a factor of two. For these reasons, the instantaneous method is used to calculate all uncertainties reported herein.

Table 1. Quantification of error with two methods for temporal averaging

Measured Quantity	Average Value (ppm)	Precision Error (ppm)	Temporal Error (ppm)	Total Error (ppm)
C_Exhaust	2200	1	138	138
C_Room	894	1	30	30
C_Ambient	624	1	7	7

Derived Quantity	Average Value (%)			Total Error (%)
Capture Efficiency (Instantaneous)	83%			1.8%
Capture Efficiency (Averaged)	83%			3.9%

3.8 Testing Procedure

In general, a typical set of tests proceeded as follows:

1) **Two to four hours were needed until the range and room came into near-thermal equilibrium**. This somewhat long period of time was needed was due to the fact that the massive emitters as well as the range mockup were increasing in temperature.

2) **After the room reached near-thermal equilibrium, CO_2 injection began, with the CO_2 process heater active, and another one half to two hours were required for the concentration field** to reach steady state- depending on the exhaust flow rate of the hood. We chose to wait no fewer than 30 minutes for the concentration to stabilize. This is greater than the four air changes suggested in Walker et al. (2016) for all flow rates tested.
3) After this, fan flow rate could be adjusted and another 0.5 to 1.5 hours was required for the concentration field to again reach steady state and another point recorded.

3.9 Experimental Program

After initial tests were performed to decide on burner specifications and operation, we attempted to identify the variables which had the greatest effect on measured capture efficiency. Literature on the subject as well as conversations with installers and manufacturers pointed to range hood flow rate; burner power (or, equivalently, temperature); burner location; and type of emitter as the salient variables. This served as the starting point for our testing program.

Preliminary tests were done with several types of emitters. These included the ASTM Emitter; a modified version of this emitter which only had the top plate, a shallow pan with tracer gas injected into water in the pan, a deeper pot with tracer gas similarly injected into water in the pot, and a perforated copper tube which was wrapped around the heating element and then a pot placed on top of it. The main outcome of these preliminary tests was that it became clear that the emitter type had much less effect on the measured capture efficiency than did the temperature of the emitter.

For this reason, the majority of the rest of the investigations looked at the combined effect of modulating burner power (or emitter temperature) and range hood flow rate. During this phase, we also looked at the effect of emitter location and (in the case of the overhead hood) hood height on capture efficiency. A few tests were done to look at the effect of using two emitters and two active burners for both types of hood tested.

4. RESULTS

4.1 Initial Investigation of Emitter Types

We first tested the performance of the range hood at the "middle" of the installation height range which was possible with manufacturer-provided hardware (28 in or 71 cm above the counter), which was also the average of the anecdotal reports we received from installers on typical installation heights in homes. These tests were performed with multiple emitter types as described above in the Methods Section in order to assess the effect of emitter type on measured performance.

Figure 6 below shows the measured capture efficiency for the five emitters tested. Tests done at flow rates less than 200 cfm (94 L/s) are not reported in this Figure or in those below except as necessary, as we did not consider them reliable for the reasons discussed above in Methods Section. All tests were done at the same input power (787 W) unless noted otherwise. For one set of experiments, we reduced the power to 464W to assess the effect on capture efficiency. This is labeled (464 W) in Figure 6. The ASTM Emitter was tested at two input powers to assess the impact of this variable. In Figures 6-11 the error bars indicate ± one standard deviation.

Figure 6 shows a somewhat surprising trend: four very different means of injecting tracer gas result in very similar measured range hood performance through the entire expected operating flow range of the range hood. However, when power to the ASTM Emitter was increased, a large deviation in measured range hood performance was observed. This trend is even greater for the single-plate emitter, which was simply the top plate of the ASTM Emitter. This seems to suggest that the amount of power input into the plume above the burner is at least as important a variable in determining range hood performance as is the range hood flow rate.

In the emitters other than the ASTM Emitter, water was being boiled and thus a significant fraction of the input power was used in the phase change of the water, leaving less energy to be transferred to the plume. The proportion of power used to boil the water was estimated by observing how much water needed to be added over a given time to maintain a fixed water depth for a boiling pot of water. Knowing the evaporation rate allows calculation of the energy required to evaporate the water at this rate using the latent heat of evaporation. In our experiments, we estimated the evaporation rate to be about 0.8 to 1.2 kg/hour, which required about 520-750 W.

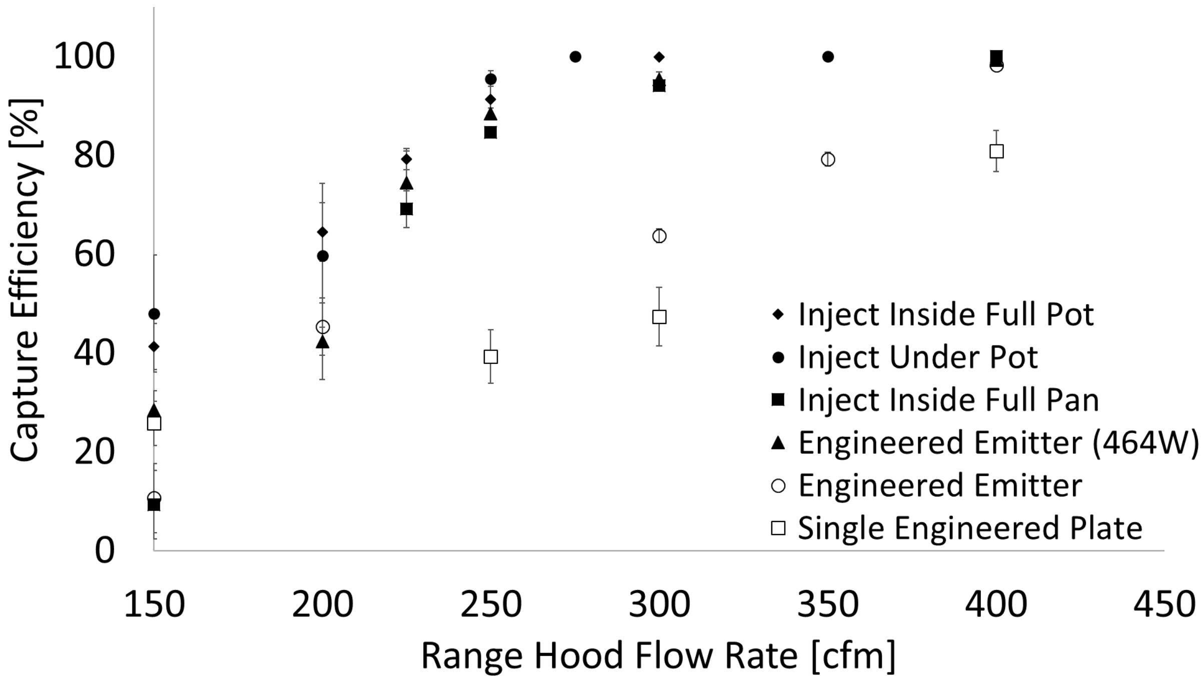

Figure 6. Results of overhead island experiments with different emitters. All tests done at 28 inch hood height, and at 787W unless noted otherwise.

4.2 Effect of Power Input

Because of the result presented in the previous section, our investigations moved strongly into looking at the combined effect of input power and flow rate on measured range hood performance. Figure 7 below shows the effect of input power variation on the measured range hood performance at three different hood flow rates. As can be seen, power has a great effect on measured performance, with the effect being stronger at lower flow rates. In general, CE decreases with power and increases with flow rate.

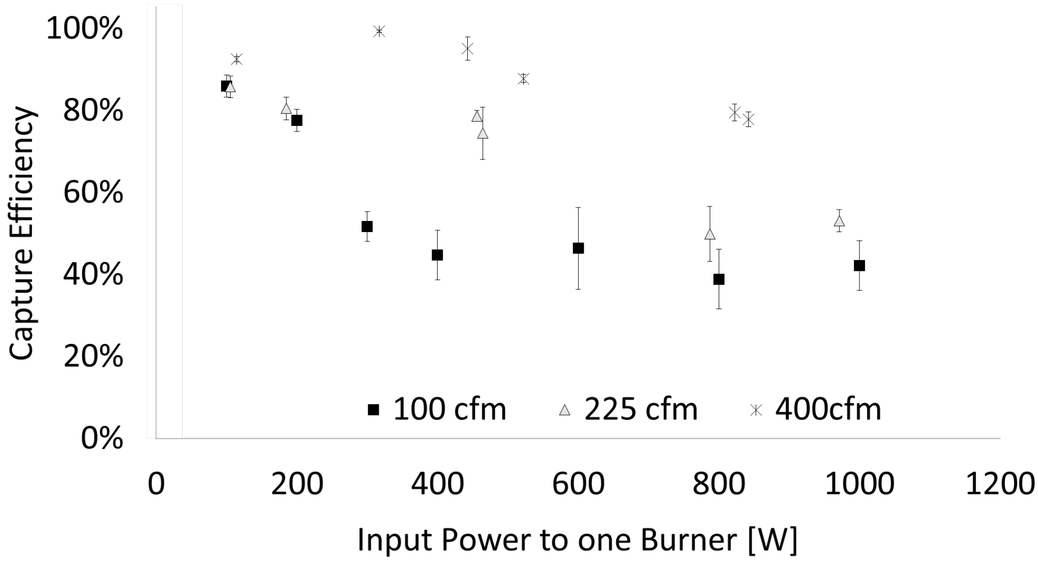

Figure 7. Effect of power input to burner at three hood flow rates. All tests performed on front left burner with 28 inch hood height

From Figure 7 we can see that simply specifying a flow rate at which testing is to be done is not sufficient, as performance varied by over 30% at the same flow rate over the input power ranges tested. One possibly more productive way to think about the relationship between the two most influential variables, input power and range hood flow rate, is through the use of a dimensionless number which contains both. Application of the Buckingham Pi Theorem may offer some useful insights. Below in Table 2 is the list of variables which we believe may influence the measured performance of the hood. We can assume diffusive properties play negligible roles in a convection-driven problem such as the one under investigation where the medium of interest is a gas. This leaves seven independent variables with four dimensions, suggesting three dimensionless variables are sufficient to describe the problem according to the Theorem.

Table 2. List of variables affecting measured capture efficiency

Variable	
$\dot{P}$	Electrical Power Input [W]
$\dot{V}$	Exhaust flow rate [m^3/s]
H	Height of range above counter [m]
Cp	Specific heat capacity [J/kg-K]
β	Coefficient of Thermal Expansion [1/K]
ρ	Density of incoming air [kg/m^3]
g	Acceleration due to gravity [m/s^2]

While any number of dimensionless numbers can be formed from the variables in Table 2, we found that the most informative way of formulating the problem was in terms of the dimensionless variable:

$$\boldsymbol{Capture\ Efficiency} = \boldsymbol{f}\left(\frac{\frac{\boldsymbol{H^3}}{\dot{\boldsymbol{V}}}}{\frac{\boldsymbol{\rho C_p H^3}}{\dot{\boldsymbol{P}}\boldsymbol{\beta}}}\right)$$

The dimensionless variable can be thought of as the ratio of the time scale for upward movement of air due to fan-driven advection and the time scale for outward thermal expansion. If we then re-plot Figure 7 with this dimensionless variable as the independent variable, we get the plot in Figure 8. The trivial cases in which the burners are off are omitted for clarity. In Figure 8, we see the three disparate curves in Figure 7 nearly collapse into one curve.

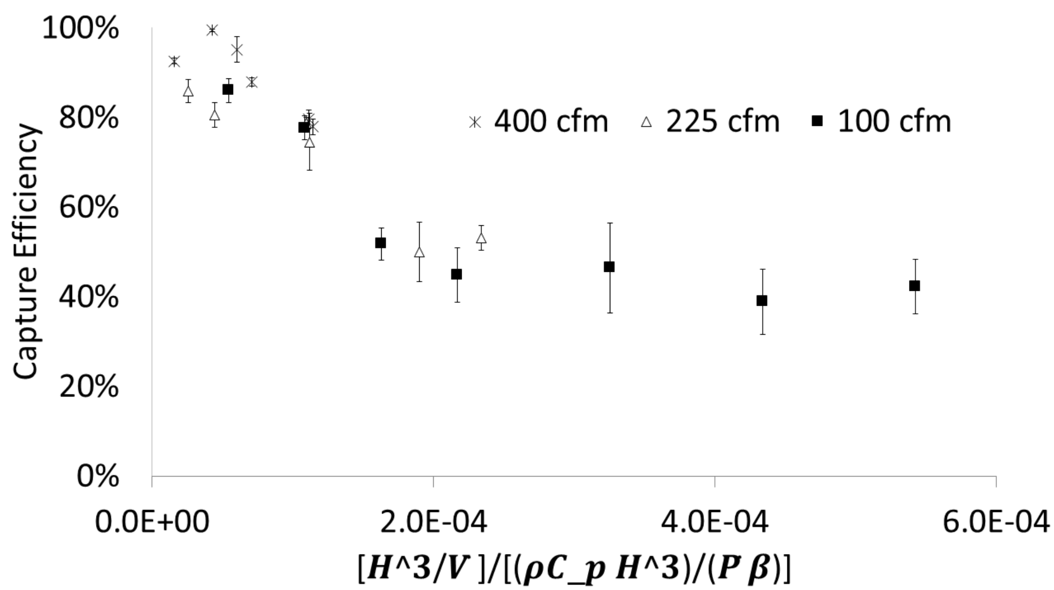

Figure 8. Re-plot of Figure 7 with dimensionless variable as independent variable

4.3 Effect of Height

We performed tests at three range hood heights in four-inch increments through the height range recommended by the manufacturer, at several levels of power input. Results for 32 inch and 24 inch (81 cm and 61 cm) hood heights (measured from range surface to hood face) are presented in Figure 9 and Figure 10, respectively. Spot checks of repeatability were performed occasionally and those results are included in these figures.

The results show some general trends. First, measured range hood performance declines with increase in power in many cases as seen previously. Depending on the flow rate tested, however, this decline in measured performance can either be drastic or only slight. This is significant in that the choice of power input and flow rate at which range hoods are to be rated in the future could have a great effect on the apparent performance of the hood. For example, tests done at high flow rates (e.g. 400 cfm (190 L/s)) with this particular hood would suggest the hood performed very well, with a capture efficiency greater than 95%, regardless of input power. However, at 300 cfm (140 L/s), the choice of power input would have a drastic effect on reported performance, with a low power suggesting range hood captured 90% or more of pollutants and a high power suggesting they capture less than 60%. No broad conclusions can be drawn about the effect of hood height.

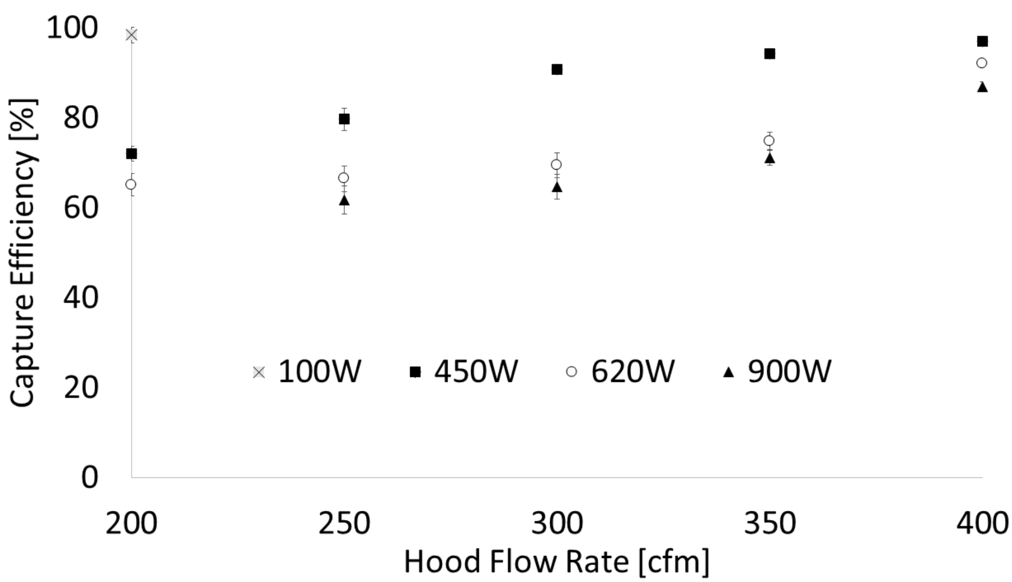

Figure 9. 32-inch hood height results

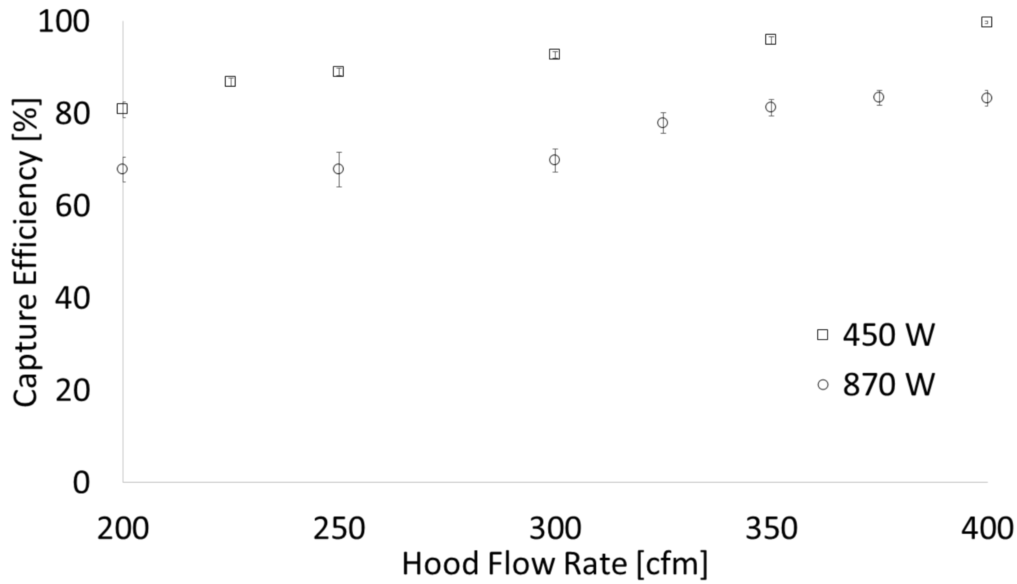

Figure 10. 24-inch hood height results

Again we can re-plot these results with the dimensionless variable suggested in Section 4.2 as the independent variable to assess its value. Because the dimensionless variable contains the height at which the range hood is set, it may in the future be possible to generate a characteristic curve for a particular range hood that would be valid for all input powers, heights, and flow rates, although this would require further study. This could greatly simplify a testing protocol by, for example, defining tests at three values of this dimensionless variable only, which defined the performance of the hood over all expected operating conditions. Figure 11 includes data from all heights tested for the overhead island range hood and suggests such a curve may be possible. Points in the shaded area are very low-power cases in which the plume likely doesn't make it all the way to the hood. Further investigations are needed to make any more conclusive statements about this normalization procedure.

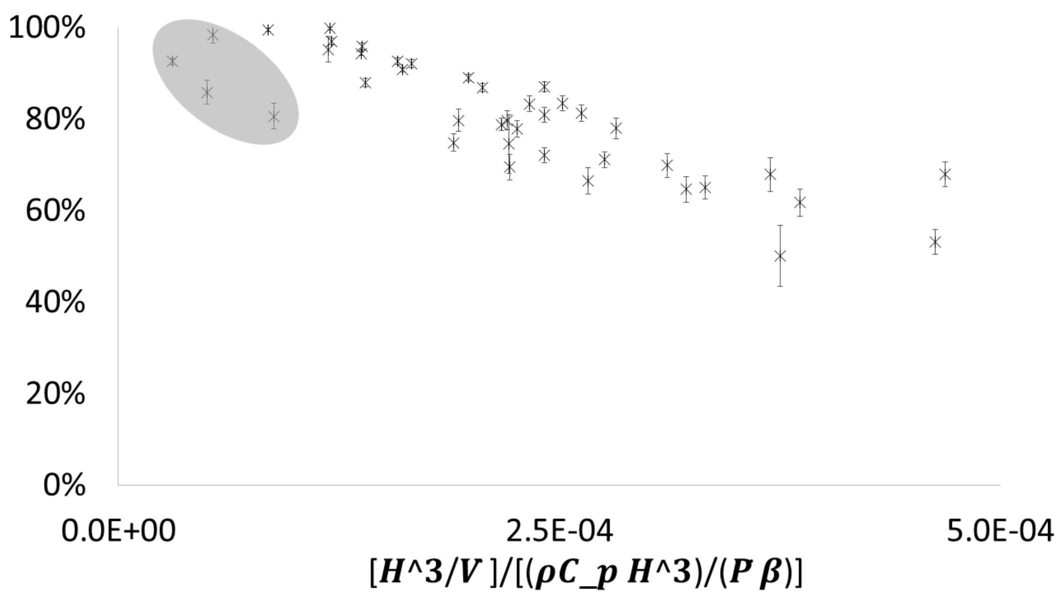

Figure 11. Data from all heights tested for overhead island range hood plotted against dimensionless variable. Shaded region is low-power cases in which the plume does not likely reach the hood.

4.4 Effect of Burner Location

We did further tests to assess the effect of burner location on measured capture efficiency and whether burner performance was symmetric with respect to midplanes of the range hood. The results in Figure 12 show the results of these tests with burner locations. All tests were performed at intermediate values of 435 W and 225 cfm (106 L/s) and at a 24-inch (61 cm) hood height. In general, corresponding right-to-left and front-to-back tests were within 3% of each other in regards to measured capture efficiency. Center burners had around 12% greater capture efficiency for the hood tested.

Centerline of Range Hood

CE [%]	ERR [%]			CE [%]	ERR [%]
77.0	1.6	Back Left	Back Right	75.7	2.0
90.7	0.4	Middle Left	Middle Right	88.1	0.6
79.6	2.0	Front Left	Front Right	76.1	2.4

Centerline of Range Hood

300mm

300mm

Figure 12. Results of burner location tests

4.5 Two Burners

In order to investigate the effects of having more than one burner operating at the same time and the resulting plume interactions, we performed experiments in which both “front” and “back” burners were turned on at 420 W each and tracer gas emitted through an ASTM Emitter on each in equal amounts. The results of this particular experiment are shown in Figure 13. Other than for very low flow rates, which were unreliable and unrepeatable for the reasons described above, the performance of the range hood under the two-burner conditions was extremely close to the performance of the single burner case. This may simplify a testing method in that at moderate power inputs and moderate flow rates, for this particular range hood, it seems one-burner performance is a good indicator of two-burner performance as well. Time did not permit testing at all power inputs to see if this behavior was replicated generally.

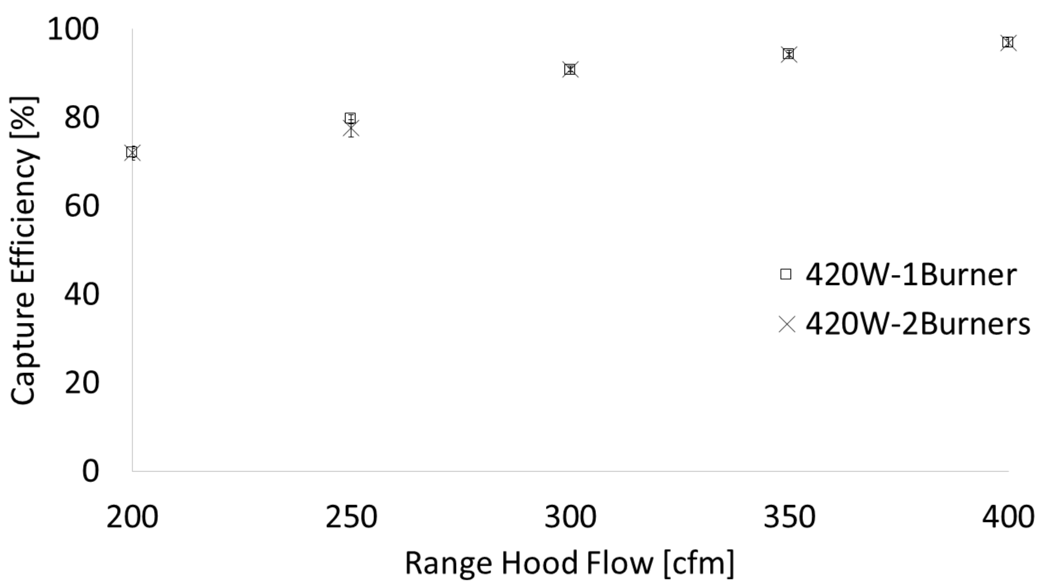

Figure 13. Effect of two simultaneous burners and emitters operating

5. Summary and Recommendations for a Test Method

The following section summarizes the lessons drawn from the construction of the experimental apparatus and the tests performed. Attempts are made to recommend aspects of testing protocol for any future standard which may be developed for rating island hoods.

Burners

In the course of our initial investigations we found exactly one commercially available burner for a reasonable price which met our conditions for performance. Any test method could either specify that this particular burner be purchased, or describe the characteristics of the burner which needed to be met. These include:

1. A simple mechanical control mechanism (no microprocessor) which allows average power readings to be consistent across experiments and which deviate less than 1% from a long-term averaging after fifteen minutes
2. Capability to produce an average of 1000 W input power without melting an aluminum emitter.
3. Commercial quality in which performance will not degrade after coil temperatures upwards of 500 °C (532 ^{o}F) are reached for hours at a time
4. Ability to fit within a mocked up range, effectively meaning housing less than 10 in. (25 cm) along its shortest edge

Alternatively, a test method could specify a specific range that needed to be purchased to conduct testing. We don't recommend this for several reasons. First, a particular range won't be modifiable with regard to burner location and a quick market survey showed that the variations in burner locations on ranges are vast. Second, a range would need a hard-wired 220V power supply which may increase the burden for those wishing to do testing.

Emitters

For the tests done for overhead island exhaust hoods, we showed to some degree that the choice of power input or temperature was a much more important variable in determining range hood performance than emitter type, and that the performance of a hood under water-filled emitters could be approximated by reducing power to an ASTM-E3087-17 emitter. For this reason, we recommend the use of the ASTM-E3087-17-specified emitter to ensure consistency across tests of different range types.

Burner/Emitter Locations

The tests we performed showed a maximum of 12% deviation in capture efficiency when tests were done at the middle of the expected range of operation in regard to flow, range height, and testing power input. We therefore recommend either a consensus testing location that is representative of the most common burner location in kitchen ranges, or the location farthest from the center of the range which can accommodate burner housing in a test rig. As mentioned, location of a "typical" burner location will be challenging as wide variation exists in available products.

Number of Burners

For overhead island exhausts, the few tests we were able to complete within this project suggested that when burners are placed with centers 24 in (60 cm) apart on a nominal 30” (76 cm) range, the plumes do not interact and one-burner results are representative of two-burner results as well. This could simplify the specification of a test method, but the generality of these results must first be assessed.

Power Supply Maximum and Averaging

We found that limiting the power supply to less than 1200 W maximum was necessary to prevent melting an aluminum emitter of the type specified in ASTM-E3087-17. This needs to be done with a variable transformer or similar device as burners maintain a given power supply by either closing and opening the circuit that contains the burner or modulating the resistance of the circuit and thus the current. We found that at the maximum setting, the cycling did not cause thermal behavior that invalidated the assumption of constant power, and did not cause problems in averaging power supply if averaging is done over a period of at least 15 minutes. The results presented herein show that range hood capture performance can be sufficiently challenged with power inputs of less than 1000 W.

Steady-state conditions and averaging

In order to ascertain that steady state conditions have been reached, surface temperature of a range or range mockup should be measured in at least two locations. Emitter surface is an obvious choice for one of these locations. We also measured significant temperature gradients across the range and range temperatures as high as 100 ^oC (210 ^oF), so another location on the range should be measured as well. The center of the range is an obvious choice. In our experience in this investigation, we found that requiring measured surface temperatures to change less than 0.1 ^oC (0.2 ^oF) between adjacent readings is achievable. Once steady state is reached, no reading should deviate more than 0.2 ^oC (0.4 ^oF) from the average over a 15-minute period.

A simple indicator of steady state in the concentration field of tracer gas experiments is much more difficult for reasons having to do with the stably periodic fluid mechanical phenomena that exist in many experiments. This only occurred in experiments conducted at flow rates less than 200 cfm (94 L/s) in our testing. Walker et al. (2017) witnessed similar phenomena, but were able to reduce this through modification of makeup air diffusers, offering another possible means of achieving good data. Rather than limiting the flow rates at which tests could be performed or diffuser type, we suggest limiting a valid result to be defined as that with temporal standard deviation of 4% or less over a fifteen-minute period or longer.

Testing conditions: Power and Flow

The testing done as part of these investigations agreed with other studies, and showed that for the same range hood flow rate and height, very different capture efficiency is measured with different power inputs to burners. Discrepancies as large as 35% in measured capture efficiency were found when all other conditions were held constant and power modified by only 300 W. One can 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. Furthermore, as the result in Figure 7 show, the relationship between the variables and capture efficiency is not obvious.

We offered above a possible path forward for dealing with this issue. This involves describing capture efficiency as a function of one dimensionless variable which contains both power and flow rate. It is conceivable that this could significantly simplify any future testing protocol, as tests could simply be performed at 2-3 values of this variable to define a curve in this single dimensionless variable (rather than testing at many values of burner power and flow rate) in order to characterize a hood under all expected operating conditions. Further study is needed to assess the generality and robustness of this method.

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