A STUDY OF THE EFFECTS OF CO_2 INJECTION RATE ON THE MEASURED CO_2 CAPTURE EFFICIENCY OF DOMESTIC KITCHEN RANGE HOODS

A Thesis

by

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ABSTRACT

Range-hood capture efficiency testing is a procedure standardized by the American Society for Testing and Materials (ASTM) with the purpose of measuring the ability of a kitchen exhaust fan to remove pollutants generated during cooking activities. The Texas A&M University RELLIS Energy Efficiency Laboratory (REEL) has developed a testing facility, which complies with the ASTM 3087-18: Standard Test Method for Measuring Capture Efficiency of Domestic Range-Hoods, in order to conduct capture efficiency research.

The main objective of this research was to determine the effect that the tracer gas injection rate has on the measured range-hood capture efficiency. Determining and analyzing this effect was then used to validate the rounding-down procedure developed at REEL for selecting the test CO_2 injection rate in standard liters per minute, and to suggest whether the ASTM injection rate bounds require a review. A secondary objective was investigating the relationship between measured capture efficiency and range-hood fan speed.

The research presented above required detailed testing of two different range-hoods with their integrated exhaust fans (Whirlpool Over-The-Counter Microwave and Venmar Under-Cabinet Range-Hood). The first objective was completed by testing one-hundred and ten (110) combinations of fan flowrates (cubic-feet-per-minute) and CO_2 injection rates (standard-liters-per-minute) across both range-hoods. These results then showed that capture efficiency decreases with an increase in CO_2 injection rate. In fact, it was observed that for most fan speeds the lowest capture efficiency was recorded at the maximum allowable CO_2 injection rate.

REEL's rounding-down procedure consists of calculating the maximum allowable injection rate in SLPM during a test (per ASTM 3087-18), and then rounding that value down to

the closest multiple of five SLPM in order to ensure that variations in the flowrate of the range-hood do not lead to testing at an injection rate greater than the maximum allowable by the ASTM standard. Initially, there were some concerns that the rounding-down procedure could lead to significant variations in capture efficiency results, but test results showed that the difference between the measured capture efficiencies at the same flowrate, but different rounded injection rates, was negligible (0.3, 2.49, and 0.69 %CE). With differences between measured capture efficiencies represented a percent difference of 0.46%, 5%, and 0.84% respectively, which allow one to conclude that REEL's rounding-down procedure does not compromise the accuracy of the reported range-hood capture efficiency. On the contrary, the large percent difference range (2% - 18%) between the measured maximum and minimum capture efficiencies at the permitted ASTM injection rate bounds suggest that the ASTM bounds might be flawed or that the OTR has intrinsic characteristics that lead to highly variable capture efficiency measurements. It is recommended to conduct more testing with additional units.

The secondary study showed that capture efficiency is proportional to the operating fan speed, meaning that capture efficiency increases as the fan speed increases. The increase in capture efficiency with respect to the change in flowrate diminishes as the flowrate increases.

DEDICATION

I would like to dedicate this thesis to my loving parents who have educated and molded me to develop into the person who I am today, and who always strive to provide me with the best opportunities available.

To my girlfriend Mariajose for always being supportive and keeping me motivated when I need it the most.

To all my friends and fellow Aggies who have shared a part in my academic journey and the countless sleepless nights through my various degrees.

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Contributors

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NOMENCLATURE

ASTM	American Society for Testing and Materials
CE	Capture Efficiency
CO_2	Carbon Dioxide
EPA	Environmental Protection Agency
IR	Injection Rate
SLPM	Standard Liters Per Minute
OTR	Over-The-Range Microwave
REEL	RELLIS Energy Efficiency Laboratory
RHCE	Range Hood Capture Efficiency

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1. INTRODUCTION

Cooking and food preparation are widespread activities performed by most adults every day. Most cooking activities such as grilling, baking, boiling, etc. release dangerous pollutants like carbon monoxide (CO) and nitrogen dioxide (NO_2) (WHO 2017). Air pollutants considerably reduce indoor air quality and can potentially create dangerous conditions for the dwellers of such residence. The National Human Activity Pattern Survey (NHAPS) reported that Americans typically spend 69% of their time in their residence (Klepeis et. al. 2001). Studies from the U.S. Environmental Protection Agency (EPA) show that human exposure to air pollutants during their time indoors may be two to five times higher than during their time outdoors (EPA 2018). In order to remove the pollutants released during cooking activities, engineers have developed range-hoods with kitchen exhaust fans, typically positioned over a stove top. The American Society of Testing and Materials (ASTM) developed a standard procedure (ASTM 3087-18: Standard Test Method for Measuring Capture Efficiency of Domestic Range Hoods) to test and evaluate the capacity of domestic range-hoods to remove contaminants from the kitchen environment (ASTM 2018). The ASTM 3087-18 defines capture efficiency (CE) as the ratio of pollutants that are captured and/or removed by the kitchen exhaust device to the pollutants that are released in the kitchen environment. The CE test utilizes carbon dioxide (CO_2) as a tracer gas to simulate the pollutants that are released during the cooking activities. The research reported on this thesis is a comprehensive study of the effect that the tracer gas (CO_2) injection rate has on the measured capture efficiency of domestic kitchen range-hoods.

The main objective of this research was to determine the effect that the tracer gas injection rate has on the measured range-hood capture efficiency. Determining and analyzing this effect was then used to validate the rounding-down procedure developed at REEL for selecting the test CO_2 injection rate (SLPM), and to suggest whether the ASTM injection rate bounds require a review.

A secondary objective was investigating the relationship between measured capture efficiency and range-hood fan speed.

1.1. Research Objectives

The objectives of this study are to determine the effect that varying the CO_2 injection rate has on the measured range-hood capture efficiency, and to evaluate the relationship between the measured capture efficiency and range-hood fan speeds. The ASTM 3087-18 standard states that the acceptable tracer gas injection rates must be between the following bounds:

1) Upper Bound: at most 0.5% of the range-hood flow rate. (e.g., 300 CFM)

$$\mathrm{CO_2}\left[\frac{\mathrm{L}}{\mathrm{min}}\right] = 300[\mathrm{CFM}] * \frac{28.32\left[\frac{\mathrm{L}}{\mathrm{min}}\right]}{1[\mathrm{CFM}]} * 0.5\% = 42.5\left[\frac{\mathrm{L}}{\mathrm{min}}\right]$$

2) Lower Bound: injection rate such that the difference between the measured exhaust and inlet concentrations of CO_2 is 100 times greater than the accuracy of the measurement device.

$$100 * \pm 15\ \mathrm{ppm} = 1500\ \mathrm{ppm}$$

In addition to adhering to the above ASTM injection rate bounds, a standard procedure has been developed at REEL to select the injection rate for a test by first calculating the maximum rate allowed, and then rounding it down to the nearest multiple of five SLPM. If the calculated maximum rate is already a multiple of five or just greater than a multiple of five, it is at the technician's discretion to test at either the rounded maximum rate or the rounded maximum rate minus an additional 5 SLPM. For example, if the maximum allowable injection rates for two different tests are 26.7 SLPM and 29.8 SLPM both would be tested at 25 SLPM. However, if the maximum rate is calculated to be 30.4 SLPM the technician may choose to test at either 30 SLPM (the rounded maximum rate) or 25 SLPM. This methodology has shown to be effective for keeping the injection rate within the acceptable bounds of the ASTM 3087-18 standard; however, until the study reported above was performed there was not a detailed investigation or evaluation of the efficacy of this newly developed procedure being implemented at REEL.

The results of this study will be used to decide if it is necessary to review the acceptable range of CO_2 injection rates presented by the ASTM 3087-18 standard, and to determine if REEL's rounding-down procedure could be skewing the capture efficiency ratings.

1.2. Test Subjects

As part of this research study, a large testing data base was obtained by performing a wide range of tests on a Whirlpool Over-The-Range microwave (OTR) and a Venmar under-cabinet range hood. The Whirlpool WMH31017HB OTR and the Venmar IU600ES30BL units were tested in their rectangular vertical discharge configurations (3 ¼" X 10"). Figures 1 and 2, reprinted from the Whirlpool and Venmar websites, present the units tested during this study.

Figure 1: Whirlpool WMH31017HB Over-The-Range Microwave Used to Create the Data Base for this Study (reprinted from Whirlpool)

Figure 2: Venmar IU600ES30BL Under-Cabinet Range Hood Used to Create the Data Base for this Study (reprinted from Venmar)

2. TEST SETUP AND METHODOLOGY

2.1. Capture Efficiency Test Equipment Setup

This research project not only used the capture efficiency test chamber of the RELLIS Energy Efficiency Laboratory (REEL) located at the Texas A&M University RELLIS campus in Bryan, Texas, but it also has as its objective to modify and upgrade the testing procedure with a focus on CO_2 injection rate. The above CE chamber was built in accordance with the ASTM-E3087-18 standard for the specific purpose of performing capture efficiency testing of domestic wall-mounted range-hoods.

The test chamber is furnished with a 0.9m tall countertop that includes two heating elements topped with custom built plume diffusion emitter plates. The emitter plates were manufactured following the specifications outlined by ASTM-E3087-18 and Figure 3, adapted from the ASTM-E3087-18 standard, shows the schematic drawing of the plates. The purpose of the heating/emitter assembly is to simulate the flow of pollution particles generated during the cooking process over a typical residential stovetop.

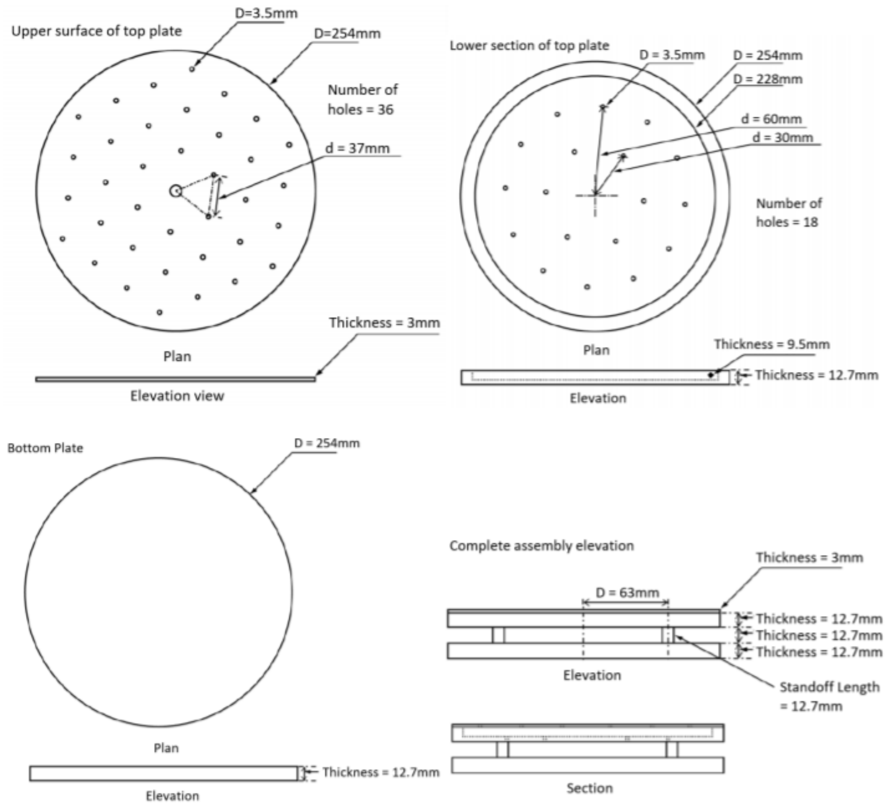

Figure 3: Plume Diffusion/Tracer Gas Emitter Assembly (adapted from ASTM 2018)

Other equipment components installed in the capture efficiency chamber includes: two wooden boxes that are used to simulate typical kitchen cabinetry, two thermocouples to measure and monitor the surface temperature of the emitter plates, two pressure transducers to measure the differential pressure along the Venturi tube to calculate the operating flowrate of the range-hood that is being tested, and a National Instruments Data Acquisition system (DAQ) that relays the signals of the thermocouples and the pressure transducers to the workstation installed outside the chamber. Figure 4, reprinted with the permission of Axel Jacquesson, presents a schematic drawing of the aforementioned capture efficiency chamber and its equipment.

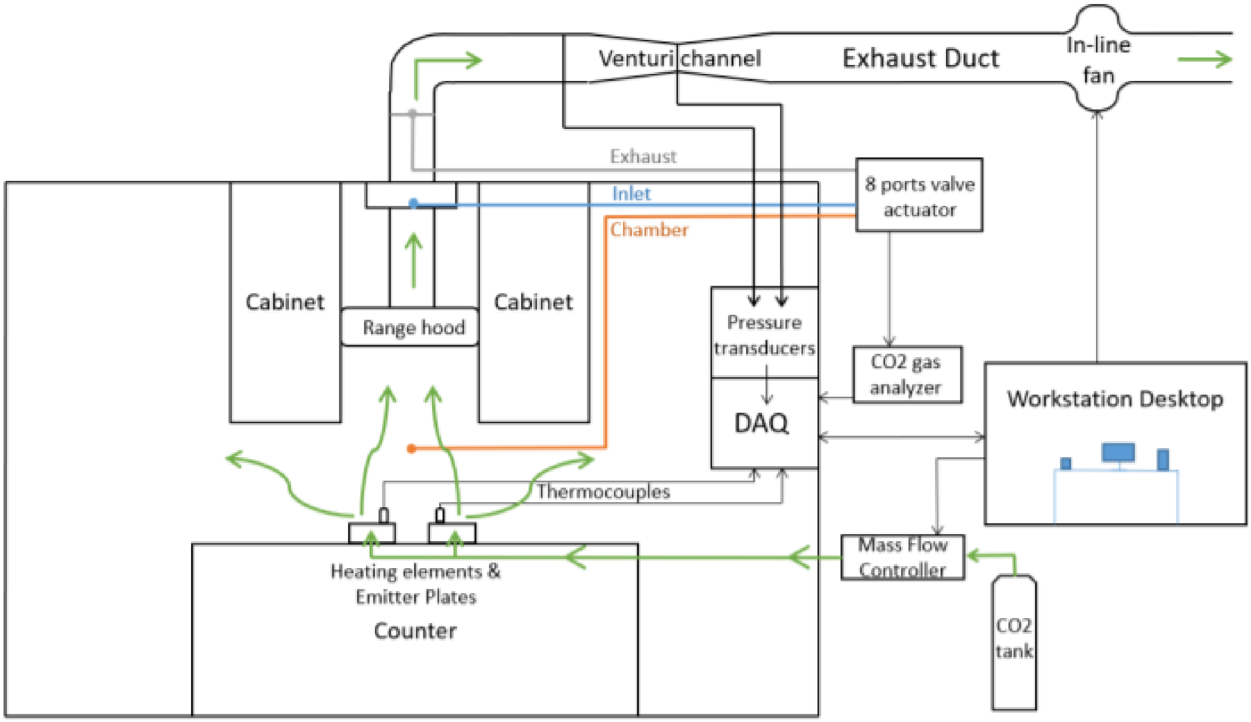

Figure 4: Capture Efficiency Test Chamber Schematic (reprinted with permission from Jacquesson 2020)

The exterior test chamber setup, which can also be seen in Figure 4, includes an in-line fan that is used to adjust the range-hood flow rate to achieve the required operating condition for the capture efficiency test. The ASTM-E3087-18 standard specifies that the CO_2 concentrations must be measured at three different locations, the inlet (ambient), the chamber, and the exhaust; plus the measurements must be taken by using the same CO_2 gas analyzer sensor, rather than a sensor for each location. The three sampling locations for measuring the CO_2 tracer gas concentrations can be seen together in Figures 5, 6, and 7, which are a front, side, and top vies of the chamber respectively. Said figures are reprinted from the ASTM-E3087-18 standard.

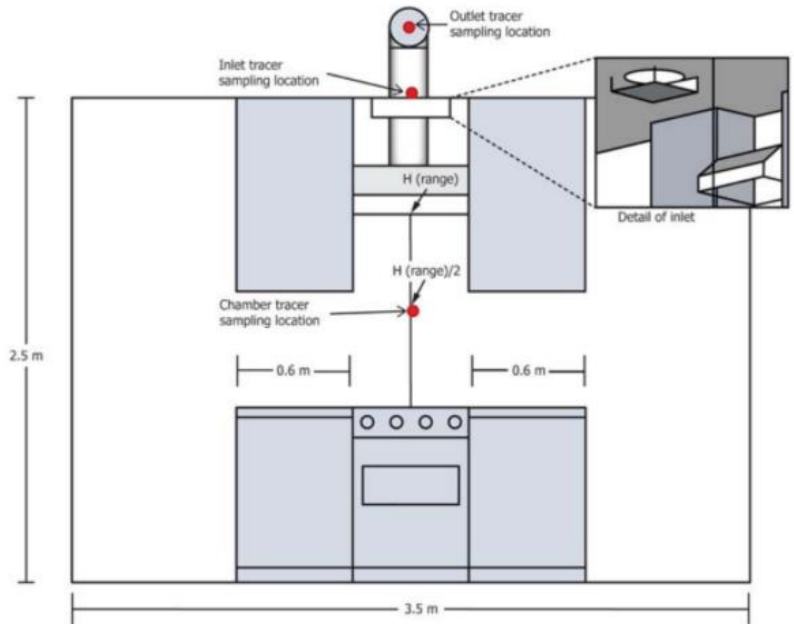

Figure 5: Capture Efficiency Chamber Front View Showing the Three CO_2 Sensing Locations (reprinted from ASTM 2020)

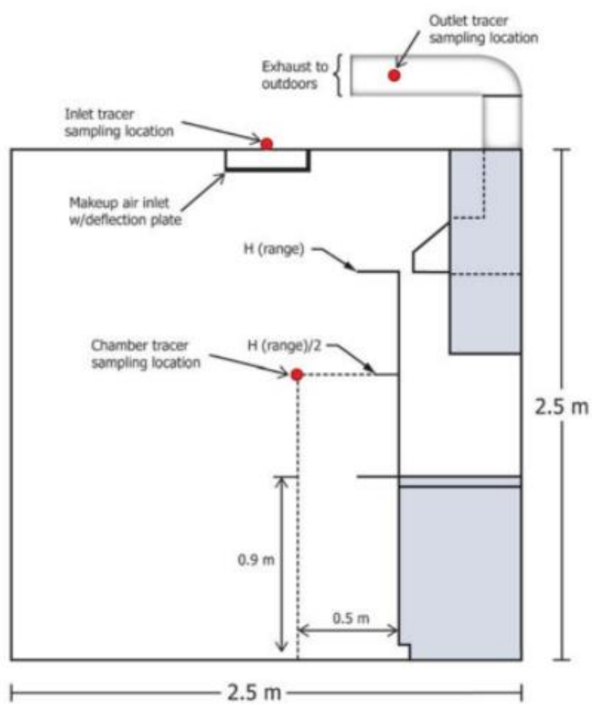

Figure 6: Capture Efficiency Chamber Side View Showing the Three CO_2 Sensing Locations (reprinted from ASTM 2018)

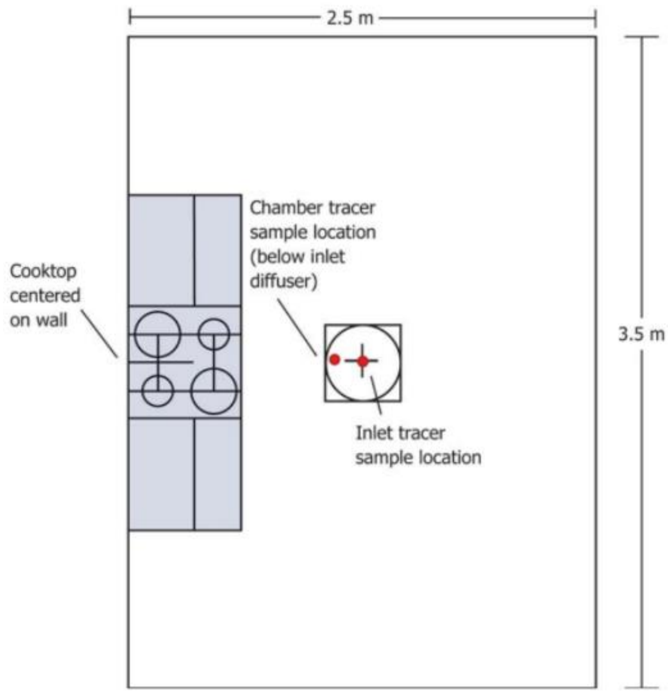

Figure 7: Capture Efficiency Chamber Top View Showing Two CO_2 Sampling Locations (reprinted from ASTM 2018)

As mentioned earlier, each sampling location is connected to the same CO_2 gas sensor with the use of an 8-port valve actuator. The valve actuator allows the testing technician to toggle between the different sampling locations and to take the desired measurements one at a time. The instrumentation also includes a mass flow controller with accuracy of less than 1% of the mass flow, and a workstation computer with the LabVIEW program to gather data and record it onto an excel spreadsheet.

2.2. Domestic Range Hood Capture Efficiency Test Methodology

The ASTM E3087-18 standard presents the accepted testing procedure to properly measure the range-hood capture efficiency. First, it is necessary to mount the range-hood between the cabinet and at the desired height above the emitter plates. This mounting is achieved by using the sliding railing system installed at the back wall of the capture efficiency chamber. It is imperative to make sure that the cabinets are perfectly flushed with the range-hood to avoid having gaps that can change the flow pattern of the tracer gas. Figure 8 shows a properly mounted range-hood ready to be tested.

Figure 8: Properly Mounted Range Hood

Second, the range-hood is turned on and allowed to run for a couple of minutes to warm up the motor and achieve a steady operational speed. Additionally, the heater plates are set to 160°C ± 10°C by using their respective Variac variable voltage transformers. A valid test requires that the heater plates stay between the specified temperature range for the entirety of the test. Given that the heater plates' temperatures tend to vary throughout the test due to the CO_2 gas and the range-hood flow, the testing technician must monitor the temperatures continually and adjust the Variacs as needed.

After the range-hood motor is warmed up, the technician has to ensure that the chamber is sealed, and its door is properly closed. Then, the tracer gas is injected at a maximum rate of 0.5% of the range-hood flow rate at which the test is being performed. The calculation presented below shows the maximum allowable injection rate for a range-hood that is operating at 300 CFM.

$$CO_2\left[\frac{L}{min}\right] = 300[CFM] * \frac{28.32\left[\frac{L}{min}\right]}{1[CFM]} * 0.5\% = 42.5\left[\frac{L}{min}\right]$$

The standard specifies that before starting to take the measurements of the CO_2 concentrations, it is necessary to allow the system to achieve steady state. The steady state condition is achieved when the capture efficiency test chamber experiences four air changes. An air change is defined as the complete removal/replacement of the air volume of the chamber. The steady state time in minutes is calculated by using the formula presented below:

$$T_{ss} = 4 * \frac{V_{chamber}\ [ft^3]}{Q_{range\ hood}\ [CFM]}$$

When the steady state condition is reached, the test can begin, and the technician is allowed to start collecting the measurements of the tracer gas concentrations. The technician records at least 10 measurements of the tracer gas concentration at the inlet, chamber, and exhaust. The minimum allowable test duration is 10 minutes. The measurements are taken using the LabVIEW software installed on the workstation desktop computer with an example being shown in Figure 9.

Figure 9: LabVIEW Software Used to Take CO_2 Measurements

After the 10 tracer gas concentration measurements for each sampling location have been recorded, the technician calculates the range-hood capture efficiency by using the three CO_2 sensor location measurements and the equation presented below:

$$\mathrm{CE} = \frac{\mathrm{C_{exhaust}} - \mathrm{C_{chamber}}}{\mathrm{C_{exhaust}} - \mathrm{C_{ambient}}}$$

The CE is measured as a percentage (%), while the $C_{exhaust}$, $C_{chamber}$, and $C_{ambient}$, which represent concentrations of CO_2, are measured in parts per million (ppm). The calculation presented above is performed by using the REEL Capture Efficiency Excel Spreadsheet, with an example being shown in Figures 10 and 11.

No.	C_inlet (ppm)	C_chamber (ppm)	C_exhaust (ppm)	CE	Q_hood (cfm)	Right Burner Temp. (˚C)	Left Burner Temp. (˚C)	Chamber Temp. (˚F)	Depressurization (i.w.c)
Taken after 4 Air Changes				#DIV/0!					
				#DIV/0!					
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	585	698	2712	94.69	348	165	143	75	0.011
	569	707	2848	93.94	348	163	144	75	0.014
1	573	692	2811	94.68	350	162	145	75	0.014
2	567	694	2812	94.34	350	161	147	75	0.014
3	580	687	2807	95.20	350	160	149	75	0.014
4	563	691	2810	94.30	350	160	151	75	0.014
5	572	693	2733	94.40	349	160	152	75	0.013
6	576	682	2777	95.18	351	160	154	75	0.014
7	565	689	2836	94.54	351	160	156	75	0.014
8	569	701	2782	94.04	349	160	158	75	0.013
9	572	704	2758	93.96	350	160	159	75	0.014
10	574	718	2839	93.64	352	159	162	75	0.013
Post				#DIV/0!					
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AVG.	571	695	2797	94.43	350	160.2	153.3	75.0	0.0137
Capture Efficiency Reported			94.43						
STDEV	5.17	10.25	33.69	0.50	0.92	0.79	5.50	0.00	0.00
COV	0.9%	1.5%	1.2%	0.5%	0.3%	0.5%	3.6%	0.0%	3.5%

$$CE = \frac{C_{exhaust} - C_{chamber}}{C_{exhaust} - C_{inlet}} \; X\ 100\%$$

Inlet			Chamber			Exhaust		
PPM	eviation	Dev²	PPM	eviation	Dev²	PPM	eviation	Dev²
573	1.9	3.61	692	-3.1	9.61	2811	14.5	210.25
567	-4.1	16.81	694	-1.1	1.21	2812	15.5	240.25
580	8.9	79.21	687	-8.1	65.61	2807	10.5	110.25
563	-8.1	65.61	691	-4.1	16.81	2810	13.5	182.25
572	0.9	0.81	693	-2.1	4.41	2733	-63.5	4032.25
576	4.9	24.01	682	-13.1	171.61	2777	-19.5	380.25
565	-6.1	37.21	689	-6.1	37.21	2836	39.5	1560.25
569	-2.1	4.41	701	5.9	34.81	2782	-14.5	210.25
572	0.9	0.81	704	8.9	79.21	2758	-38.5	1482.25
574	2.9	8.41	718	22.9	524.41	2839	42.5	1806.25

Configur 350 cfm, 22.5 lpm

Standard Error Calculation					
Inlet		Chamber		Exhaust	
Mean	571.1	Mean	695.1	Mean	2796.5
Sum Dev	240.9	Sum Dev	944.9	Sum Dev	10214.5
Std. Dev	5.17365	Std. Dev	10.2464	Std. Dev	33.6889
Std. Error	1.63605	Std. Error	3.2402	Std. Error	10.6534
$\delta_{..}$	1.63605	$\delta_{..}$	3.2402	$\delta_{..}$	10.6534
$\delta_{.}$	0	$\delta_{.}$	8.68875	$\delta_{.}$	0
δ	1.63605	δ	9.27326	δ	10.6534
Capture Efficiency Uncertainty			0.007822864		
apture Efficiency Uncertainty [%			0.782		

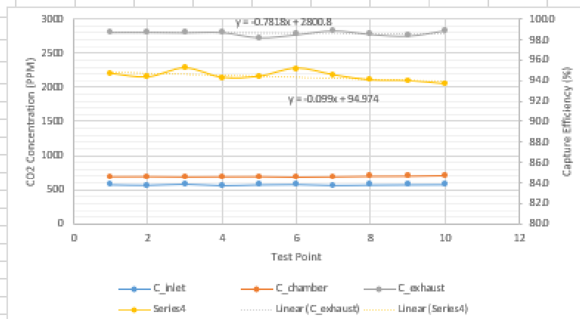

Figure 10: REEL Capture Efficiency Excel Spreadsheet

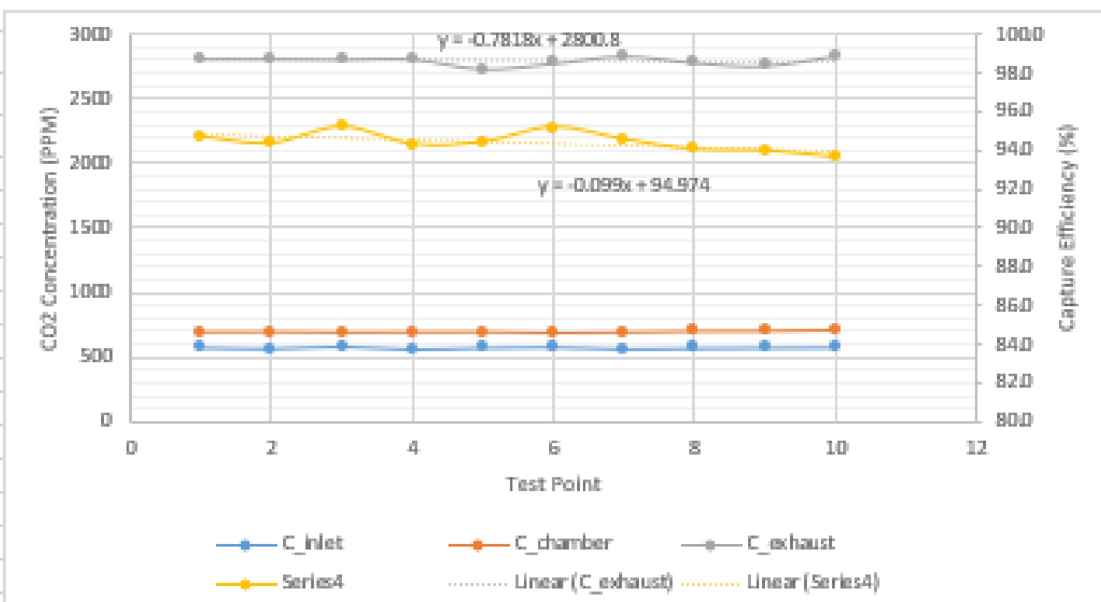

Figure 11: Measured Capture Efficiency Plot for Each Test Data Point

The REEL Capture Efficiency Excel Spreadsheet is used to calculate the measured range-hood capture efficiency and to keep historical records of all the tests performed at the laboratory. The graph at the lower right corner of Figure 10 and enlarged on Figure 11 presents the CE values at each measured point (yellow curve) and the CO_2 concentrations at the inlet, chamber, and exhaust (blue, orange, and grey, respectively). These curves allow the technician to determine if the testing conditions have stayed stable throughout the test. In order to accept the test, the CE curve must have a slope in the range of ± 0.15 [%CE]. If the absolute value of the slope is greater than 0.15 [%CE], the technician must continue taking measurements until the slope of the CE curve falls inside the acceptable bounds.

3. CO_2 INJECTION RATE STUDY DEFINITION

The previous section defined range-hood capture efficiency (RHCE) as the ratio of pollutants that are captured and removed by the range hood to the pollutants that are released in the kitchen during the cooking process. In order to calculate the RHCE of a unit, carbon dioxide is used as a tracer gas to simulate the pollutants that are released into the kitchen environment (test chamber). This section presents the effect that the tracer gas (CO_2) injection rate (IR) has on the measured capture efficiency of domestic kitchen range hoods.

3.1. Testing Scope

The scope of this study includes the following:

- Correlation between capture efficiency and CO_2 injection rate.
- Validation of REEL's rounding-down standard procedure to select the injection rate.
- Analysis of the tracer gas injection rate bounds specified by the ASTM 3087-18 standard.
- Relationship between capture efficiency and range hood fan speed.

3.2. Testing Procedure

The CO_2 injection rate study followed the ASTM 3087-18 standard and the testing methodology presented in the previous section. Both test subjects were tested at several fan speeds and at different tracer gas injection rates. The Whirlpool OTR was tested at a total of four speeds: 250 CFM, 218 CFM, 201 CFM, and 120 CFM, while the Venmar range-hood was tested at two speeds: 350 CFM and 300 CFM. Table 1 presented below summarizes the speed setting and flowrate of each of the Whirlpool and Venmar units.

Table 1: OTR and Range Hood Speed Settings

Whirlpool WMH31017HB		**Venmar IU600ES30BL**	
Speed (CFM)	**Speed Setting**	**Speed (CFM)**	**Speed Setting**
250	HS (2/2)	350	HS (3/4)
218	HS (2/2)	300	HS (3/4)
201	HS (2/2)	--	--
120	LS (1/2)	--	--

Both units were tested at injection rates between 2.5 SLPM and 45 SLPM. Special attention was given to the injection rates between 20 and 30 SLPM, as this is the most common range encountered during range-hood capture efficiency testing. In addition to the injection rates tested across all the speeds, the Whirlpool OTR was tested at the maximum injection rate allowable per the ASTM standard for the flowrates achieved at high speed (HS 2/2). Forty-three different operating conditions were tested for the Whirlpool microwave across its four flowrates, while the Venmar range-hood was tested at twenty-two different operating conditions across its two flowrates. Table 2 presents the full summary of the combinations of operating speeds and injection rates that were tested during this study.

Table 2: Summary of the Testing Combinations

	Whirlpool WMH31017HB				Venmar IU600ESBL	
Operating Speed	**250 CFM**	**218 CFM**	**201 CFM**	**120 CFM**	**350 CFM**	**300 CFM**
CO2 Injection Rate (SLPM)	2.5	2.5	2.5	2.5	2.5	2.5
	5	5	5	5	5	5
	10	10	10	10	10	10
	20	20	20	20	20	20
	22.5	22.5	22.5	30	22.5	22.5
	25	25	25	35	25	25
	27.5	27.5	27.5	40	27.5	27.5
	30	30	28.5	45	30	30
	35	30.8	30	--	35	35
	35.4	35	35	--	40	40
	40	40	40	--	45	45
	45	45	45	--	--	--

The large amount of testing combinations, sixty-five combinations between both units, created a considerable time constrain that made it infeasible to test all the combinations more than once. Even though several of the tests were performed more than once, the results that did not appear abnormal and followed the expected trends were not retested. The sixty-five testing combinations ended producing one-hundred and ten (110) valid range hood capture efficiency tests. These test results are presented and analyzed in the following sections.

4. CO_2 INJECTION RATE STUDY EXPERIMENTAL RESULTS

4.1. Whirlpool WMH31017HB OTR RHCE Test Results

The Whirlpool unit was extensively tested, and its forty-four test combinations resulted in eighty-three data points. The experimental results are broken out by their flowrate and presented on Tables 3 through 6. The blue side of the tables show the measured capture efficiency at each iteration of a specific test (CE1, CE2, and CE3), while the green side of the tables present a brief statistical analysis of the results of the tests with multiple iterations. The statistics include the average capture efficiency (CEavg), standard deviation (St Dev), and the coefficient of variance (CV) of the tests at each injection rate. The coefficient of variance was computed in order to scale the magnitude of the standard deviation and to present the variability of the data in a more intuitive way.

Table 3: Whirlpool OTR 250 CFM Flowrate Test Results

IR (SLPM)	CE1 (%)	CE2 (%)	CEavg (%)	St Dev	CV (%)
2.5	70.86	69.13	70.00	1.22	1.75
5	69.83	--	69.83	--	--
10	68.17	70.77	69.47	1.84	2.65
20	63.93	66.97	65.45	2.15	3.28
22.5	72.15	--	72.15	--	--
25	70.13	--	70.13	--	--
27.5	68.52	--	68.52	--	--
30	64.82	--	64.82	--	--
35	64.52	--	64.52	--	--
35.4	63.82	--	63.82	--	--
40	63.98	63.9	63.94	0.06	0.09
45	66.08	66.43	66.26	0.25	0.37

Table 4: Whirlpool OTR 218 CFM Flowrate Test Results

IR (SLPM)	CE1 (%)	CE2 (%)	CE3 (%)	CEavg (%)	St Dev	CV (%)
2.5	63.90	63.71	--	63.81	0.13	0.21
5	63.74	62.03	--	62.89	1.21	1.92
10	68.21	64.98	--	66.60	2.28	3.43
20	62.93	--	--	62.93	--	--
22.5	61.70	--	--	61.70	--	--
25	57.90	62.81	60.10	60.27	2.46	4.08
27.5	62.20	63.38	56.75	60.78	3.54	5.82
30	57.33	--	--	57.33	--	--
30.8	55.94	--	--	55.94	--	--
35	59.12	60.43	58.09	59.21	1.17	1.98
40	55.12	56.30	62.78	58.07	4.12	7.10
45	57.29	61.55	--	59.42	3.01	5.07

Table 5: Whirlpool OTR 201 CFM Flowrate Test Results

IR (SLPM)	CE1 (%)	CE2 (%)	CE3 (%)	CEavg (%)	St Dev	CV (%)
2.5	54.74	55.42	--	55.08	0.48	0.87
5	56.28	59.61	--	57.95	2.35	4.06
10	60.30	58.08	--	59.19	1.57	2.65
20	57.36	--	--	57.36	--	--
22.5	53.75	53.63	56.50	54.63	1.62	2.97
25	54.15	56.55	58.31	56.34	2.09	0.04
27.5	49.48	51.96	56.94	52.79	3.80	7.20
28.5	53.78	--	--	53.78	--	--
30	56.18	52.36	--	54.27	2.70	4.98
35	55.24	51.93	49.48	52.22	2.89	5.54
40	57.20	54.09	54.91	55.40	1.61	2.91
45	55.76	54.31	--	55.04	1.03	1.86

Table 6: Whirlpool OTR 120 CFM Flowrate Test Results

IR (SLPM)	CE1 (%)	CE2 (%)	CE3 (%)	CEavg (%)	St Dev	CV (%)
2.5	34.24	33.84	33.39	33.82	0.43	1.26
5	40.06	34.73	38.38	37.72	2.73	7.22
10	31.04	36.00	38.54	35.19	3.81	10.84
20	37.06	--	--	37.06	--	--
30	38.49	--	--	38.49	--	--
40	38.88	--	--	38.88	--	--
45	37.49	37.45	--	37.47	0.03	0.08

4.2. Venmar IU600ES30BL RHCE Test Results

The Venmar under-cabinet range-hood proved to be a more consistent unit, and its capture efficiency results had a flat and consistent trend. This led to considerably less retests, such that the twenty-two test combinations resulted in twenty-seven data points. Tables 7 and 8 present the test results of the 350 CFM and 300 CFM test series for the Venmar range hood. The coefficient of variance and low standard deviation support the observation of low variation during this unit's tests.

Table 7: Venmar Range Hood 350 CFM Flowrate Test Results

IR (SLPM)	CE1 (%)	CE2 (%)	CE3 (%)	CEavg (%)	St Dev	CV (%)
2.5	95.04	--	--	95.04	--	--
5	96.08	--	--	96.08	--	--
10	93.52	--	--	93.52	--	--
20	94.23	--	--	94.23	--	--
22.5	94.43	--	--	94.43	--	--
25	93.25	--	--	93.25	--	--
27.5	92.29	--	--	92.29	--	--
30	92.22	--	--	92.22	--	--
35	92.94	93.09	--	93.02	0.11	0.12
40	92.85	--	--	92.85	--	--
45	92.66	94.17	94.50	93.78	0.98	1.05

Table 8: Venmar Range Hood 300 CFM Flowrate Test Results

IR (SLPM)	CE1 (%)	CE2 (%)	CE3 (%)	CEavg (%)	St Dev	CV (%)
2.5	93.30	--	--	93.30	--	--
5	94.89	--	--	94.89	--	--
10	89.77	--	--	89.77	--	--
20	84.34	--	--	84.34	--	--
22.5	84.41	--	--	84.41	--	--
25	83.93	--	--	83.93	--	--
27.5	82.98	--	--	82.98	--	--
30	83.39	--	--	83.39	--	--
35	82.85	--	--	82.85	--	--
40	82.92	80.79	82.77	82.16	1.19	1.45
45	84.18	--	--	84.18	--	--

5. CO_2 INJECTION RATE ANALYSIS OF RESULTS

In order to visualize the capture efficiency results, the data presented on Tables 3 through 6 was plotted on Figure 12 and the data presented on Tables 7 and 8 was plotted on Figure 13. Both plots were created using the non-averaged raw data to observe if data points land on the trendlines of different flowrates.

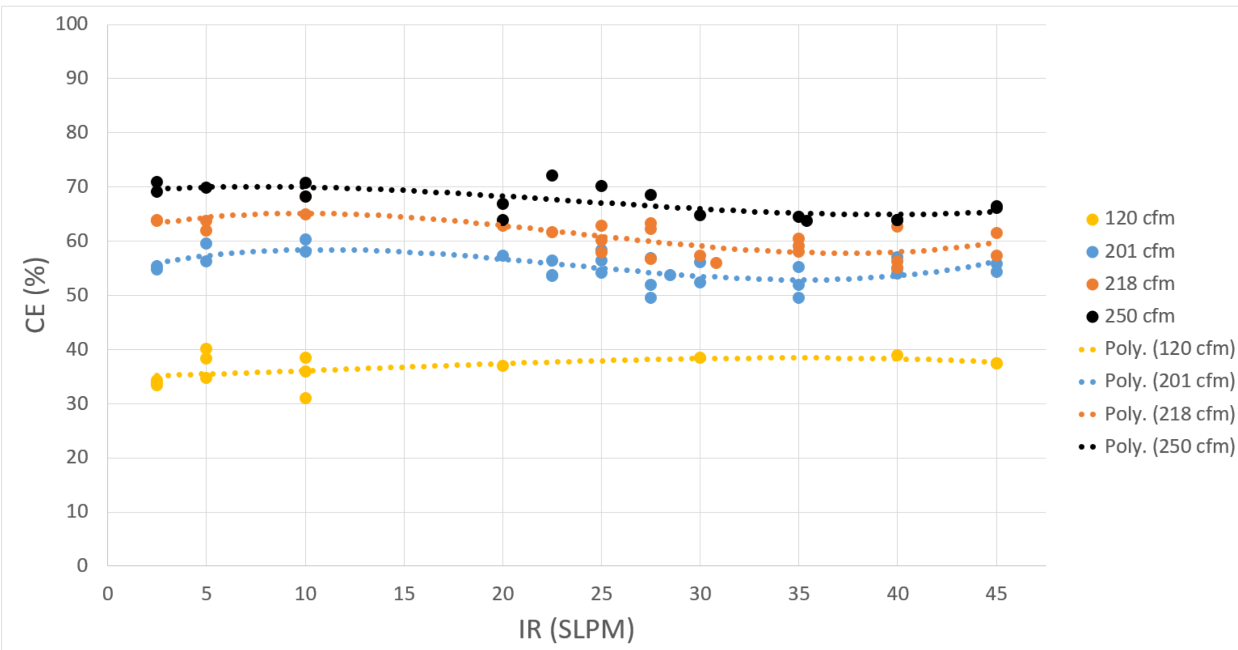

Figure 12: CO_2 Injection Rate vs Capture Efficiency – Whirlpool OTR

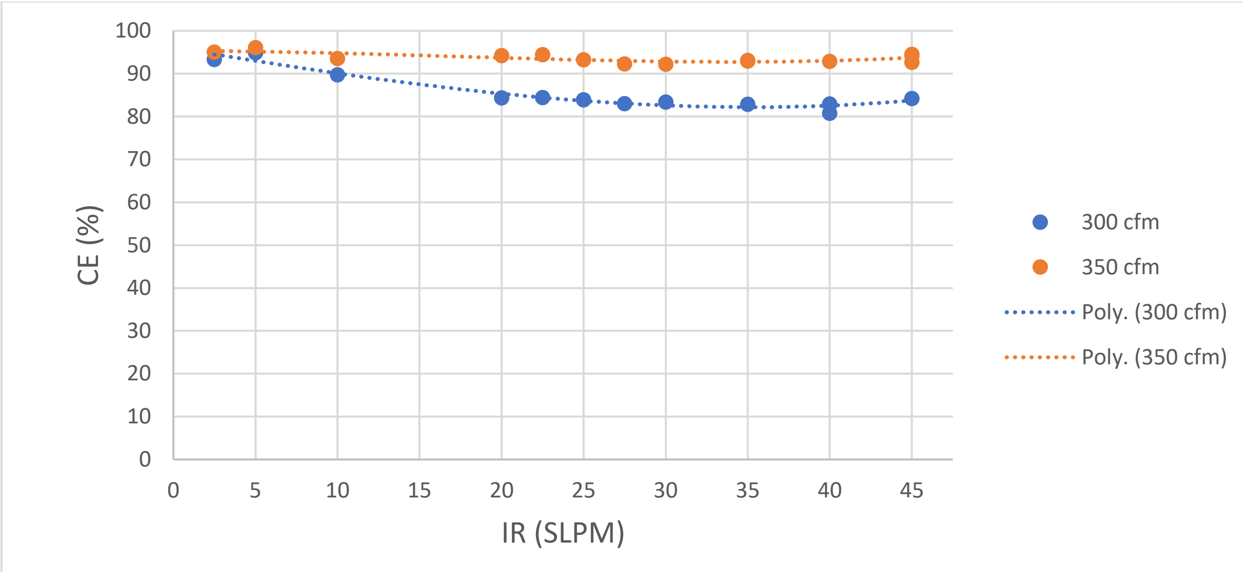

Figure 13: CO_2 Injection Rate vs Capture Efficiency – Venmar Range Hood

The capture efficiency results presented in Figures 12 and 13 show a consistent trend between the high-speed tests of both units. First, the measured capture efficiency of each flowrate follows a path roughly defined by a third-degree polynomial. Second, there appears to be three different sections along the trendline.

5.1. Capture Efficiency vs Injection Rate Trend at High-speed

At the start of the trendline, there is a slight increase in measured capture efficiency in the range from 2.5 to 10 SLPM for the OTR and from 2.5 to 5 SLPM for the range hood. This is followed by a roughly linear decrease until the maximum acceptable injection rate (per the ASTM 3087-18 standard) is reached. Finally, the third section of the trendline presents another increase in the measured capture efficiency. Figures 14 through 16 show to broken out sections of the trendline as mentioned above.

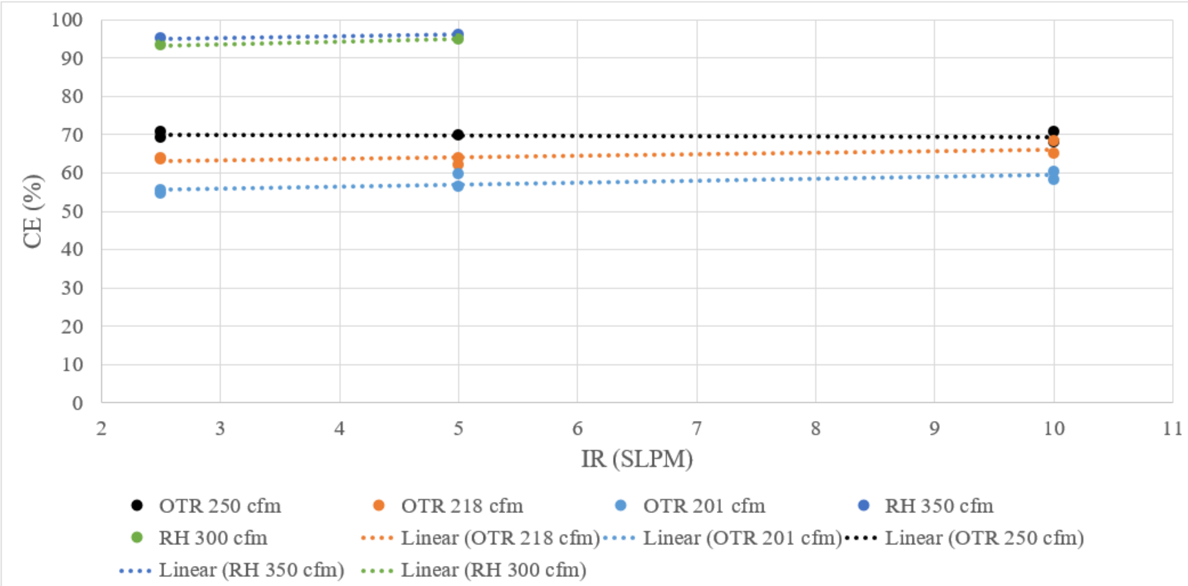

Figure 14: First Section of the Trendline

As mentioned above, the first section of the trendline presents an increase in the measured range-hood capture efficiency as the CO_2 injection rate increases. Four of the five flowrates clearly show the positive relationship between capture efficiency and injection rate, while the 250 CFM setting of the OTR portrays a flat trendline.

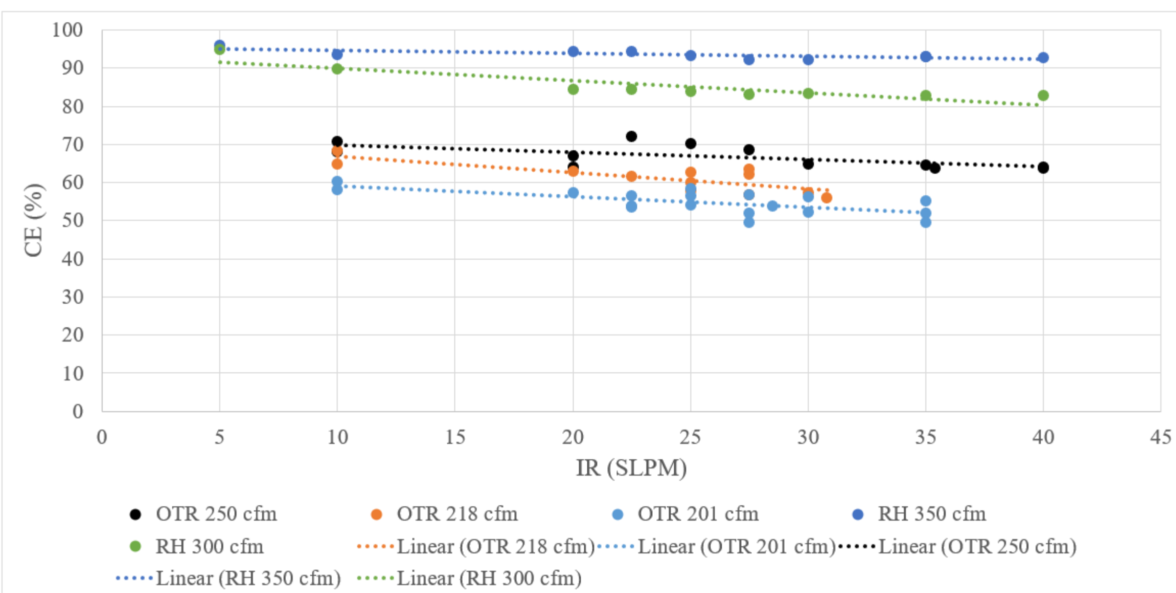

Figure 15: Second Section of the Trendline

The second section of the trendline shows a clear downward trend, which signifies that there is an inverse relationship between the capture efficiency and the injection rate. Three of the tested flowrates (OTR 201 CFM, RH 350 CFM, and RH 300 CFM) have data points that follow the downward trendline closely, but the other two flowrates behave more erratically.

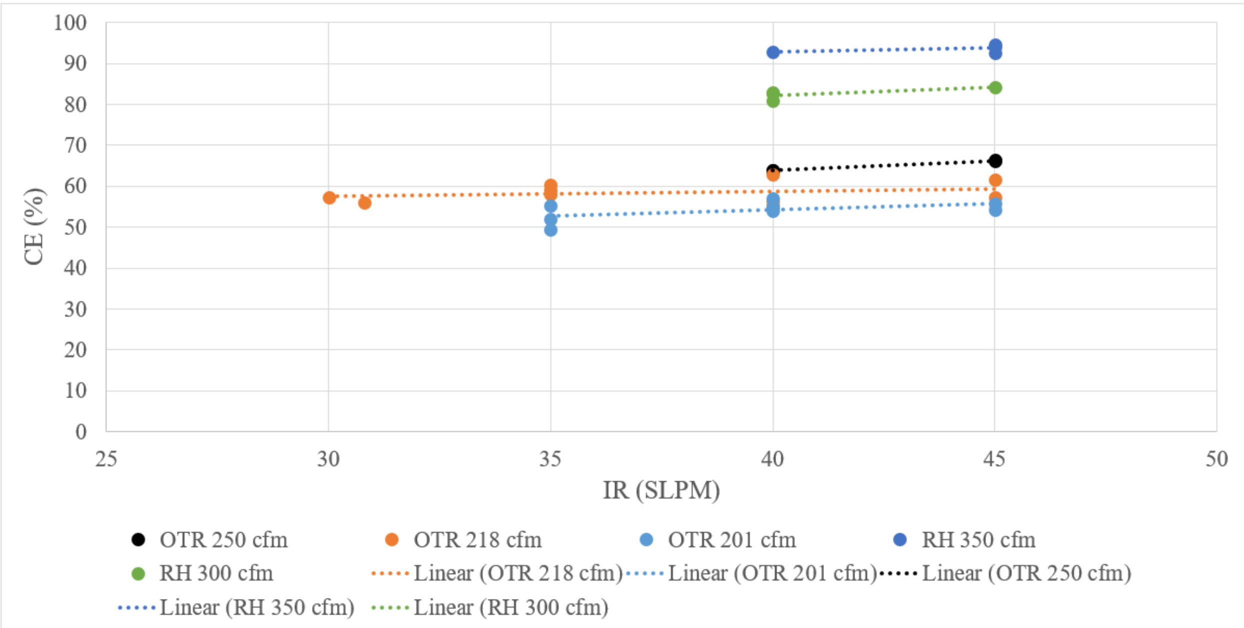

Figure 16: Third Section of the Trendline

The third section of the trendline shows an inflection point that leads to an upward trend. Increasing the injection rate produces a higher capture efficiency in this area. Given that different trends were discovered, it is not possible to reach a conclusion, at this moment, on the effect that varying the tracer gas injection rate has on the measured capture efficiency, so a deeper analysis is needed.

5.2. Flow Regime of the Tracer Gas Used During the Capture Efficiency Testing

It is believed that the flow regime of the CO_2 could have an impact on the measured capture efficiency. To test this theory, the Reynold's number was calculated for the flow through the CO_2 inlet tube, which has an inner diameter of approximately ⅛ of an inch. Flows with a Reynold's number below 2000 are generally accepted to be laminar and those with a Reynold's number greater than 10,000 are generally accepted to be turbulent. Flows with a Reynold's number between these two numbers could potentially show behaviors of either a laminar or a turbulent flow, so data collected in this region may be anomalous and uncertain. As shown in Figure 17, the injection rate of 2.5 SLPM is within the laminar flow region while the rates of 5 and 10 SLPM are in the transition region. While all other injection rates tested are well within the purely turbulent region, these three points have the potential to cause doubt in the overall results. The 2.5 and 5 SLPM data points were subsequently omitted from the analysis. The 10 SLPM data points were kept since 10 SLPM is a valid injection rate (per ASTM 3087-18) for the Whirlpool OTR when it is tested at its 120, 201, and 218 cfm settings.

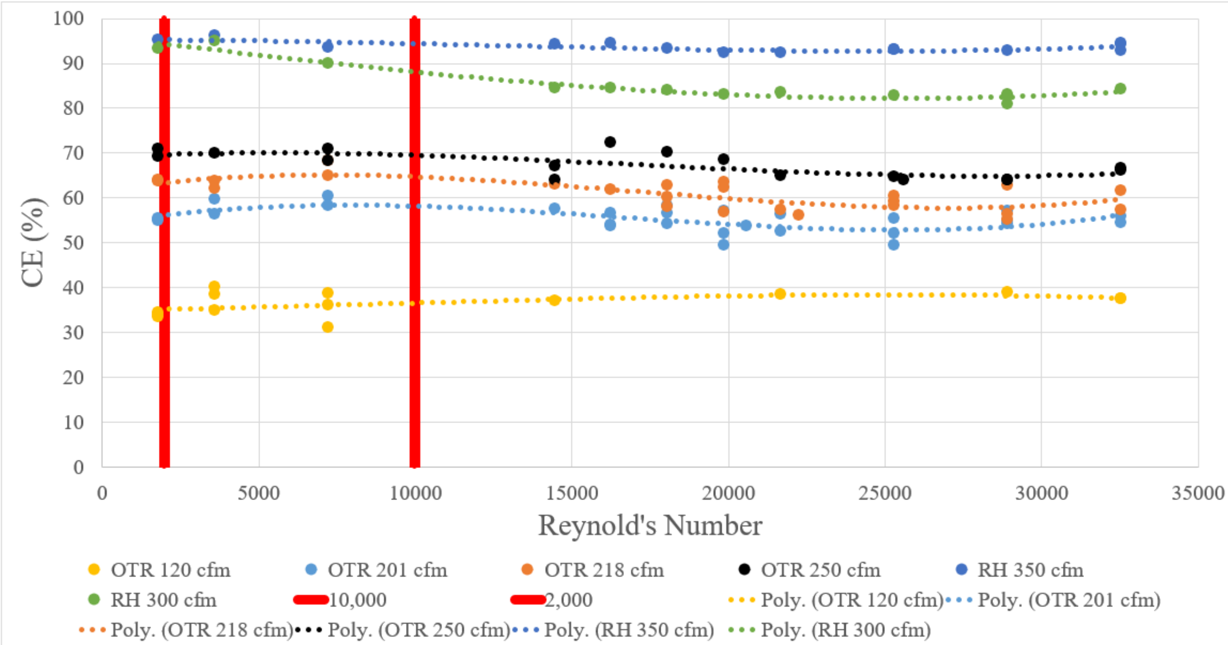

Figure 17: Capture Efficiency vs Reynold's Number with Transition Region Demarcation

After omitting the transition region data, the averaged data at each point tested was plotted to observe trends in and above the testing regions specified by the standard.

5.3. Capture Efficiency vs Injection Rate with Injection Rates Approved by the ASTM Standard

The final overall plot of capture efficiency versus injection rate is shown in Figure 18. In this plot, the results at the maximum injection rate allowed at each given speed are noted with diamond markers, points above the allowable range are noted with small square markers, points that adhere to the injection rate selection method used by REEL are denoted by triangle markers, points below the minimum injection rate are noted with red circles, and all other points are circles. It should be noted that only one of the tests performed at 120 cfm (10 SLPM) satisfy the ASTM standard's requirements, which is why those results are not plotted in Figure 18. With the anomalous transition data removed, each trend appears to follow a quadratic curve, as displayed by the trendlines plotted.

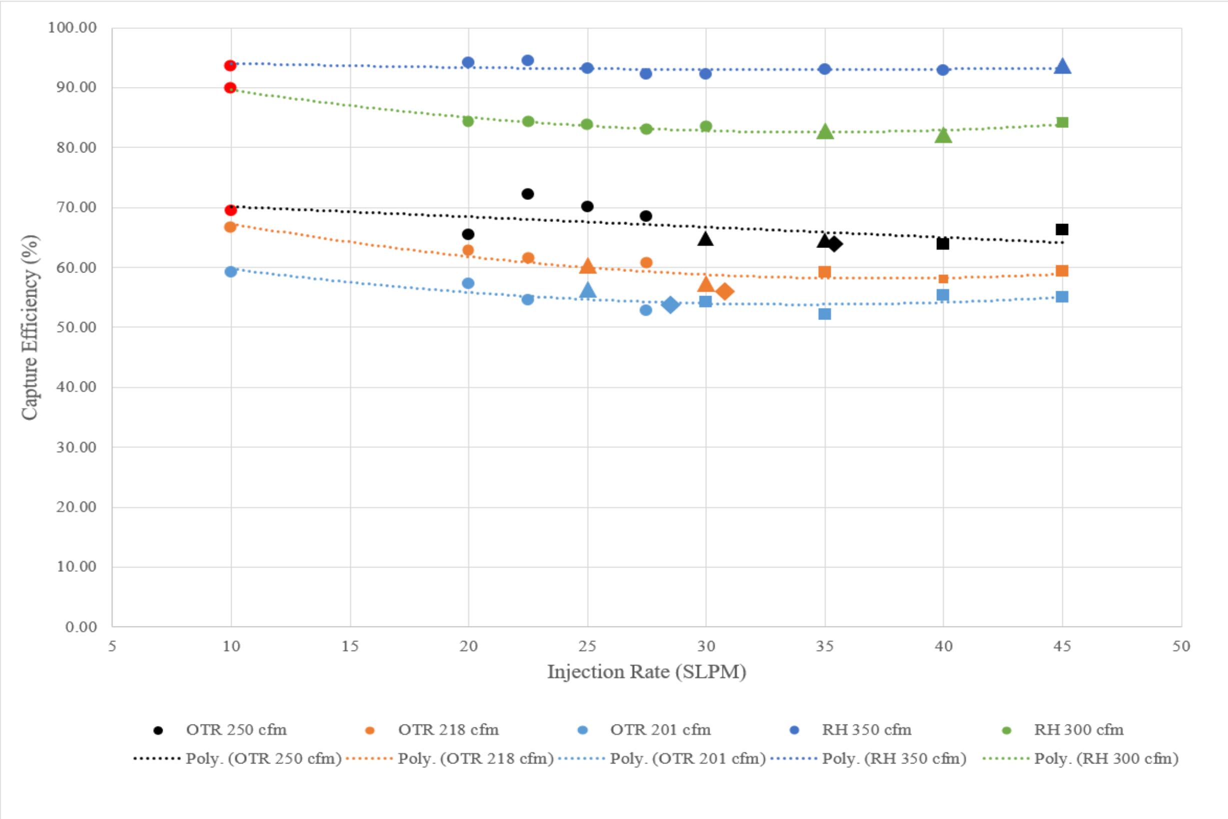

Figure 18: Plot of the Average Capture Efficiency vs CO_2 Injection Rate

After analyzing the quadratic trendline, it was possible to observe that there appears to be a localized minimum close to the maximum allowable injection rate. All the different flowrate tests across both units show strong evidence that range-hood capture efficiency is inversely related to the tracer gas injection rate. Also, the lower flowrates (201 and 218 cfm) show a greater variation between the capture efficiency measured at the maximum allowable CO_2 injection rate and the capture efficiency calculated at the typical REEL injection rates. Table 9 presents the measurement statistics of the Whirlpool OTR along the ASTM approved range of injection rates for each flowrate condition.

Table 9: Whirlpool WMH31017HB ASTM Approved Injection Rate Range Statistics

	250 cfm	218 cfm	201 cfm
AVG	67.06	60.79	55.68
STDEV	3.22	3.53	2.39
N	7	7	6
MAX	72.15	66.60	59.19
MAX-AVG	5.09	5.80	3.51
MAX%	1.08	1.10	1.06
MIN	63.82	55.94	52.79
AVG-MIN	3.24	4.85	2.89
MIN%	0.95	0.92	0.95
RANGE	8.33	10.66	6.40
RANGE/AVG	0.12	0.18	0.11

The test statistics of the Whirlpool OTR are concerning due to the large range of capture efficiency values that are measured using the injection rates specified by the ASTM 3087-18 standard. For example, the capture efficiencies calculated for the 218 CFM setting range from 55.94% to 66.60% across seven different tracer gas injection rates. This means that the spread of the computed capture efficiencies is 10.66 [%CE], which is a significant variation. When the spread is normalized by the average magnitude of the measured capture efficiencies, it can be observed that the ratio of the range to the average capture efficiency is 0.18 or 18%. An eighteen percent difference between capture efficiency values that would be used to officially rate a range-hood should not be acceptable. The statistical analysis of the capture efficiency measurements was replicated for the Venmar range-hood, and the results are shown on Table 10.

Table 10: Venmar IU600ESBL ASTM Approved Injection Rate Range Statistics

	350 cfm	300 cfm
AVG	93.26	83.44
STDEV	0.83	0.84
N	8	7
MAX	94.43	84.41
MAX-AVG	1.17	0.97
MAX%	1.01	1.01
MIN	92.22	82.16
AVG-MIN	1.04	1.28
MIN%	0.99	0.98
RANGE	2.21	2.25
RANGE/AVG	0.02	0.03

The Venmar range-hood's capability of capturing the CO_2 appears to be more consistent and less variable with respect to the injection rate. The 300 CFM testing sequence had the widest range, but it was much narrower than the ranges for the Whirlpool OTR. The ratio of the spread with respect to the average was 0.03 or 3%. This is a good result considering that most experimental applications have acceptable errors of approximately 5%.

5.4. REEL's Standard Procedure for Selecting Appropriate Injection Rate Analysis

As mentioned in Section 1, REEL's standard procedure to select the injection rate for a test consists on calculating the maximum injection rate (i.e. 34 SLPM) allowed by the ASTM standard, and then rounding it down to the nearest multiple of five (i.e. 30 SLPM). If the calculated maximum rate is already a multiple of five or just marginally greater than a multiple of five (i.e. 30.6 SLPM), it is at the technician's discretion to test at either the rounded maximum rate (i.e. 30 SLPM) or the rounded maximum rate minus an additional 5 SLPM (i.e. 25 SLPM). Given that subsection 4.3. (presented above) discovered the issue of a large range of acceptable capture efficiency measurements through the accepted ASTM injection rate bounds, it is important to determine if REEL's rounding down procedure also suffers from a wide range of results. This would not be ideal because it could lead to issues were one technician decides to perform a test at the rounded maximum rate (i.e. 30 SLPM) while another technician performs the test at the rounded maximum minus the additional 5 SLPM (i.e. 25 SLPM), and then the rated capture efficiency for the same unit could be off by a significant percentage. From the capture efficiency results gathered for the previous section, it was determined that three different test sequences (OTR 250 cfm, OTR 218 cfm, and RH 300 cfm) could potentially be tested at two different CO_2 injection rates per REEL's rounding down procedure. Table 11 summarizes the comparison between the rounded maximum injection rate and the rounded maximum injection rate minus 5 SLPM.

Table 11: Summary of REEL's Injection Rate Rounding Down Procedure

	OTR 250 cfm	OTR 218 cfm	RH 300 cfm
ASTM MAX (SLPM)	35.4	30.8	42.5
IR1 (SLPM)	35	30	40
IR2 (SLPM)	30	25	35
CE1 (%)	64.52	57.33	82.16
CE2 (%)	64.82	60.27	82.85
RANGE	0.30	2.94	0.69
% DIFF	0.46	5.00	0.84

Two out of the three eligible data sets have a percent difference lower than one percent. This means that both measurements can be used as rated values for the unit without creating misleading results. The OTR 218 cfm test setting had a higher percent difference (5%), but it could be argued that a five percent difference between values is acceptable for experimental data.

5.5. Range Hood Flowrate and Its Effect on Capture Efficiency

Figure 18 presented above gives the first hint about the effect that the flowrate has on capture efficiency. It is possible to observe that as the flowrate increased the curve of the measured capture efficiencies is higher up on the graph. This means that as the flowrate increases the range-hood capture efficiency also increases. In order to aid the visualization of the results, the capture efficiency obtained from each of the injection rates that comply with the ASTM standard was plotted for each unit. Figure 19 presented below shows the trends of the capture efficiency with respect to flowrate.

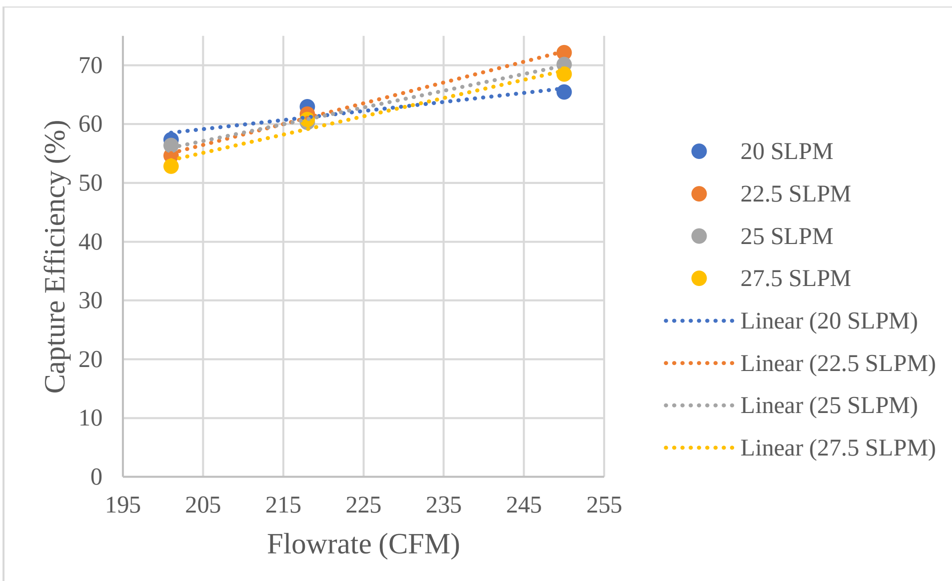

Figure 19: Whirlpool WMH31017HB Capture Efficiency vs Flowrate

All the curves have upward trends, but the slopes of the trendlines do not appear to be consistent. Figure 20 presents the trends of the capture efficiency with respect to flowrate for the Venmar range-hood.

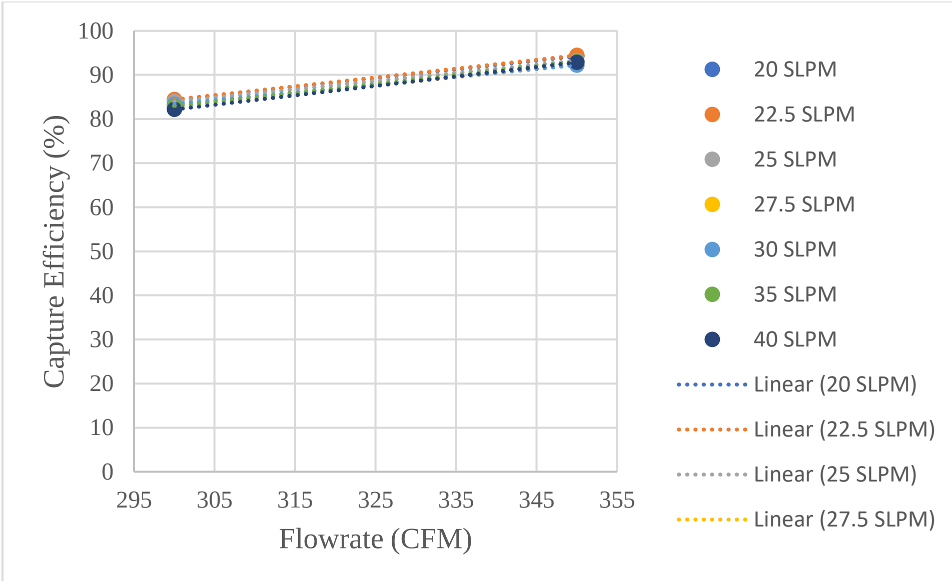

Figure 20: Venmar IU600ES30BL Capture Efficiency vs Flowrate

The plot of the Venmar under-cabinet range-hood follows the same upward trend observed on the Whirlpool OTR results, but in this case the trendlines appear to be extremely consistent. Even though the trendlines seem to be parallel, it is impossible to determine that just by observing the plot. To confirm the consistency of the trendlines, the slope of each capture efficiency vs flowrate curve was computed and presented on Table 12.

Table 12: Slope of the Capture Efficiency vs Flowrate Curves

	201-218 CFM	218-250 CFM	300-350 CFM
	dCE/dQ	dCE/dQ	dCE/dQ
20 SLPM	0.33	0.08	0.20
22.5 SLPM	0.42	0.33	0.20
25 SLPM	0.23	0.31	0.19
27.5 SLPM	0.47	0.24	0.19
30 SLPM	--	--	0.18
35 SLPM	--	--	0.20
40 SLPM	--	--	0.21

The computed slopes of the Venmar range hood are presented on the green column of Table 12. As observed on Figure 19, the slopes of the capture efficiency vs flowrate curves are basically the same and have an average value of 0.2 ∆CE/∆CFM. These results are extremely consistent, and the positive value of the slopes confirm that range hood capture efficiency is proportional to the flowrate of the Venmar range hood.

The computed slopes of the Whirlpool OTR are presented on the blue columns of Table 12. The slopes are not consistent, and they do not appear to have a clear pattern. All the slopes are positive and have average values of 0.36 ∆CE/∆CFM and 0.24 ∆CE/∆CFM for the 201 to 218 CFM case and 218 to 250 CFM case, respectively. As mentioned above, the positive slope signifies that capture efficiency increases as the flowrate increases. Also, it is important to note that the magnitude of the increase in capture efficiency with respect to the increase in the range-hood flowrate diminishes as the flowrate increases.

6. CONCLUSION

This research study's main objective was split into three sub-objectives with all three producing results that can significantly improve the established capture efficiency testing procedures. First, the effect that the CO_2 injection rate has on the measured capture efficiency of a domestic range-hood was determined and analyzed. Second, REEL's rounding-down procedure used for selecting the injection rate during standard testing was validated. Third, the injection rate bounds defined by the ASTM 3087-18 were analyzed to determine if they need to be reviewed and modified. In addition to the three components of the main objective, a secondary objective of this research study was to investigate and develop the correlation between capture efficiency and range hood fan speed.

The CO_2 injection rate study determined that the range hood capture efficiency measurements can be divided into three regions, with each region having its unique individual trend. First, extremely low tracer gas injection rates, such as 2.5 and 5 SLPM, exhibit an upward trend in which capture efficiency increases as the CO_2 injection rate increases. Data points in this low injection rate region are not valid under the specifications set forth by the ASTM 3087-18 standard, because the injection rate does not produce the standard-specified concentrations of CO_2 at the sampling locations. Second, at the other end of the spectrum, namely at high injection rates (typically above 35 SLPM), which are above the maximum allowable tracer gas injection rate per the ASTM standard, an upward trend in capture efficiency occurred, similar to what was also observed in the low injection rate region. Finally, the allowable tracer gas injection rate range per the standard, which lies between the above two extremes, resulted in an opposite trend. Specifically, in the accepted CO_2 injection rate range (10 to 35 SLPM), the range-hood capture efficiency decreases as the CO_2 injection rate increases. An interesting observation is that in three out of the five operating flowrates analyzed in this study, the minimum capture efficiency occurred at the maximum allowable tracer gas injection rate, which is consistent with the trends presented above for the three injection rate regions.

REEL's rounding-down procedure consists of calculating the maximum allowable injection rate in SLPM during a test (per ASTM 3087-18), and then rounding that value down to the closest multiple of five SLPM in order to ensure that variations in the flowrate of the range-hood do not lead to testing at an injection rate greater than the maximum allowable by the ASTM standard. An analysis of REEL's rounding-down procedure was performed herein by using the data file acquired during the previous CO_2 injection rate study discussed above. Specifically, two different flowrate conditions (250 and 218 CFM) for the Whirlpool OTR unit and one flowrate condition (300 CFM) for the Venmar under-cabinet range-hood unite were analyzed in detail to determine if REEL's rounding-down procedure could lead to inaccurate range-hood capture efficiency results. The measured capture efficiency results of the Whirlpool OTR operating at 250 CFM are 64.52%CE (non-rounded SLPM injection rate) and 64.82%CE (using REEL's SLPM rounding-down procedure), while the capture efficiency results of the 218 CFM setting are 57.33%CE (non-rounded down SLPM injection rate) and 60.27%CE (using REEL's SLPM rounding-down procedure). The percent difference between the non-rounded down and the rounded-down capture efficiencies for the 250 CFM and 218 CFM flowrates are calculated to be 0.46% and 5%, respectively.

The capture efficiency results obtained from the Venmar range-hood operating at 300 CFM are 82.16%CE (non-rounded SLPM injection rate) and 82.85%CE (using REEL's SLPM rounding-down procedure), which display a percent difference of 0.84% between the non-rounded down and rounded-down injection rate capture efficiencies. The maximum percent difference between the non-rounded down and the rounded-down capture efficiencies is 5%, which is an acceptable difference for experimental results. The results show that REEL's rounding-down standard procedure used to select the injection rate is validated and thus acceptable, meaning it does not compromise the accuracy of the reported range-hood capture efficiency.

In addition to verifying the above REEL's injection rate selection procedure, the bounds of acceptable tracer gas injection rates specified by ASTM 3087-18 were analyzed. The Whirlpool OTR results show that the capture efficiency ranges (CE at minimum allowable injection rate minus CE at maximum allowable injection rate) are 8.33%CE (based on 72.15% - 63.82%), 10.66%CE (based on 66.60% - 55.94%), and 6.40%CE (based on 59.19% - 52.79%) for the 250 CFM, 218 CFM, and 201 CFM settings, respectively. Another interpretation of the above data is the percent difference between the maximum and minimum capture efficiencies at the three separate flowrates, while still following the acceptable injection rate guidelines are 12% (250 CFM), 18% (218 CFM), and 11% (201 CFM). The large variability between measured capture efficiencies while still being within the allowable range of ASTM tracer gas injection rates should be cause for great concern. In other words, using acceptable tracer gas injection rates following the standard can produce significantly different capture efficiency ratings.

The Venmar range-hood results show that the capture efficiency ranges are 2.21% (based on 94.43% - 92.22%) and 2.25% (based on 84.41% - 82.16%) for the 350 CFM and 300 CFM settings, respectively. The percent difference between the maximum and minimum capture efficiencies following acceptable ASTM injection rates guidelines are 2% (350 CFM) and 3% (300 CFM). The variability of the capture efficiency results obtained here for the Venmar range-hood are smaller than the variabilities for the Whirlpool OTR. Of special note, the inconsistency of the capture efficiency results for two different units, based on different technologies, makes it difficult to determine if the ASTM injection rate bounds need to be altered, so it is suggested to perform the same study with several other units to determine if the large variability across the range of acceptable injection rates is an issue of the unit or if it is a flaw of the ASTM standard, which could have a wide and significant impact on range-hood industries.

The last research topic studied and reported in this thesis as a secondary objective is the relationship between capture efficiency and range-hood fan speed. Consistent with past studies, it was found that the range hood capture efficiency is proportional to the range hood fan speed, which means that capture efficiency increases as the range hood's flowrate increases. The results of the average increase in capture efficiency per unit increase in flowrate, which is $\Delta CE/\Delta CFM$ for the data are as follows: 0.36 $\Delta CE/\Delta CFM$ when increasing from 201 CFM to 218 CFM (Whirlpool OTR), 0.24 $\Delta CE/\Delta CFM$ when increasing from 218 CFM to 250 CFM (Whirlpool OTR), and 0.20 $\Delta CE/\Delta CFM$ when increasing from 300 CFM to 350 CFM (Venmar range-hood). It is important to note that the magnitude of the increase in capture efficiency with respect to the increase in the range-hood flowrate diminishes as the flowrate increases.

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