AN EXPERIMENTAL STUDY OF NEW RANGE-HOOD PERFORMANCE METRICS TO SUPPORT ENERGY SAVINGS AND STANDARD/CERTIFICATION DEVELOPMENT

A Dissertation

by

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ABSTRACT

In this dissertation, a test facility for measuring capture efficiency (CE) of residential range hoods was built and used to conduct experiments investigating the effects of multiple test factors (e.g. cook-top temperature, mounting height and discharge orientation) on CE as well as its repeatability, reproducibility and variability. The test facility described herein is the first built from the ground up following guidelines specified by a newly developed standard (ASTM-E3087.18), with one other test facility existing in the open literature that was built prior to and then used to develop ASTM-E3087.18. Although, ASTM-E3087.18 provides a standard method for measuring method for CE, there are no ASHRAE/HVI standard/certification procedures for minimum/allowable range hood CE requirements.

Three performance metrics were developed to describe CE repeatability (ΔCE) and reproducibility (α and β), with ΔCE emphasizing back-to-back tests, while α/β involve a mandatory dismount/re-mount between tests. Results showed that dismounting/re-mounting a range hood provides a more accurate representation of CE as indicated by the narrower range of values for the reproducibility metrics (α/β) of 0-4.9%CE (max.) versus the repeatability metric (ΔCE), which showed a range of 0-5.6%CE. An adapted test procedure where CE is monitored until the 10 measurements specified by ASTM-E3087.18 vary by less than 1.5%CE was found to reduce CE uncertainty and improve repeatability/variability. The variability (ε), which is a measure of the standard deviation relative to the mean, was less than 3.5% for all tests utilizing the modified test procedure except cases with a low mounting height and re-circulating vents on the range hood creating leakage.

Other results for CE and its repeatability/variability, showed cook-top temperature had a significant effect on CE, changing it by as much as 9.2%CE, with some range hoods showing CE increasing with temperature and others showing a decrease. However, even at temperatures outside those previously prescribed by ASTM-E3087.18 (i.e.130˚C), the repeatability/variability was unaffected by cook-top temperature. Mounting height also had a significant effect on CE, with lower heights increasing CE and reducing uncertainty, by as much as 7.9%CE and 0.5%CE, respectively, at the expense of worsened variability performance. It is recommended that future ASHRAE/HVI test standards continuously monitor CE, specify cabinet dimensions from the counter-top and require sealing of re-circulation vents. Additionally, it is recommended that future certification tests incorporate a mandatory dismount/remount and specify an intermediate mounting height.

DEDICATION

I would like to dedicate this dissertation to future generations. I hope that the contents of this study, as well as my time at Texas A&M University, will inspire the scientists and engineers of tomorrow to create a more sustainable future for generations to come.

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TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

CHAPTER I

INTRODUCTION

Dissertation Organization

The contents of this dissertation are organized into separate chapters that describe the various topics covered during this study. Chapter I is an introductory chapter that outlines the background, problem statement and objectives of this dissertation. Chapter II presents a literature review of studies used to quantify rangehood capture efficiency (CE) performance, with particular emphasis given to studies that are either similar or were used to develop a new American Society of Testing and Materials (ASTM) test procedure for wall-mounted, residential rangehood CE. Chapter III describes the ASTM test method, facility and procedure, as well as presenting some of its shortcomings. Chapters IV through VII consist of journal papers that are either published, submitted for review or in the process of being prepared for submission. Chapters IV presents the design, construction and verification of the first test facility following the guidelines provided by the ASTM, while also imploring additional measures to address the ASTM test method shortcomings. Chapters V – VI investigate and address the influence of various factors influencing CE, with Chapter V focusing on factors associated with details of the test procedure/facility configuration and Chapter VI focusing on factors associated with the rangehood test configuration. Chapter VII presents how the findings of this study were used to develop a new rangehood certification procedure for the Home Ventilating Institute (HVI), and how this HVI certification procedure differs from the

ASTM test method. Finally, Chapter VIII presents an overview of the conclusions drawn from this study, with Chapter IX suggesting some recommendations for future studies.

Background and Problem Statement

According to many building regulations, kitchen ventilation systems play an important role in whole-resident ventilation in that they remove moisture, odors, contaminants, and carbon dioxide generated while cooking. Although many building regulations require kitchens to have a window, a window alone is not enough to remove all the airborne contaminants that are created during cooking. Therefore, most kitchens are also equipped with a range exhaust hood to assist in removing cooking contaminants.

A range exhaust hood (i.e. rangehood) is a device that contains a mechanical fan that hangs above the stove in a kitchen and connects to ducting that exhausts to the outdoors. There are multiple testing criteria and rating standards to evaluate the airflow, loudness and power consumption of a rangehood. For example, the American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) standard 62.2 recommends a minimum flow of 100 cfm and maximum sound rating of 3 sone (ASHRAE, 2017), whereas the Home Ventilating Institute (HVI) rangehood consumer guide recommends an airflow rate of 100 cfm per linear foot of rangehood width (HVI, 2006). As one can see, ASHRAE and HVI have established a standard rating systems for airflow testing, sound testing and power consumption measurements; however, there is no standard rating system for the capture efficiency (CE), which is defined as the percentage of the total emissions from the stove top that are captured and/or vented by the rangehood. In fact, it is only recently that a standard for CE has been promulgated as discussed below.

The American Society of Testing and Materials (ASTM) recently developed a standard test method, namely ASTM-E3087.18: Standard Test Method for Measuring Capture Efficiency of Domestic Range hoods (ASTM, 2018) for measuring CE of domestic, wall-mounted rangehoods. This test method was developed with input from members of a working group consisting of rangehood manufacturers, researchers and potential users of the test procedure. However, there is only one public institution to date that has published data by using a testing facility that adheres to this new ASTM test method, namely, Lawrence Berkeley National Lab (LBNL), one of the primary developers of this standard.

Even though research data has been published by LBNL that includes experimental and field studies on rangehood performance (Singer, 2012 and Delp, 2012), there is a lack of experimental research that utilizes testing procedures that follow guidelines presented in the newly developed ASTM standard. Specifically, there are no published CE studies that utilize the ASTM standard exactly as it is written. Furthermore, the number of CE experimental studies performed that are even remotely close to the ASTM procedure, are limited to only two studies, with each utilizing a controlled laboratory setting and a known concentration of tracer gas to determine CE of a household rangehood (Walker, 2016 and Kim, 2017); however, both of these studies deviated from the ASTM standard while being performed.

For example, Walker (2016) used the same formula to calculate CE that is specified by the ASTM, and described herein, but did not use the CO2 emitter plates specified by the ASTM. Walker's study consisted of testing eight different units with 27 unique height and flow rate combinations for all units. Kim (2017) used the same procedure described by the ASTM, as well as the same emitter plates, but did not always use the same burner placement specified by the ASTM. It is important to note that several past studies have shown that burner type and configuration can have a significant effect on CE measurement and variability (Singer, 2012 and Kim, 2017). Kim's study consisted of testing two different rangehoods, with one tested at three speeds and one at a single speed, along with two different mounting heights for each rangehood.

The results from the above Walker and Kim studies performed at LBNL were used to develop key aspects of the ASTM standard, including details of the test facility and the test procedure, such as emitter plate design, burner type, cook-top temperature, chamber inlet, required air changes, sensor placement and sampling rate (Kim, 2018). Based on this fact and evaluations of past studies, it can be concluded that the recently developed ASTM standard has yet to be subjected to long-term repeatability testing, susceptibility in variations between labs and finally verification with multiple sets of data.

Additionally, the fact that the ASTM standard is the first test method for determining the performance criteria of domestic wall-mounted rangehood using a tracer gas, as well as being the first test method to quantify rangehood CE, it is important that the standard be tested in various settings to ensure its accuracy and repeatability. Furthermore, due to the complexity of multiple parameters that influence CE, it is important that particular attention is given to minimizing the effects of these parameters while performing CE testing, and also learning how to utilize them from a design standpoint to optimize energy efficiency.

Objectives

The objectives of this dissertation are described as follows:

1. Perform a review of current test methodologies used to evaluate the CE of residential, wall-mounted rangehoods over the last decade; specifically, those that are remotely close to ASTM-E3087.18.
2. Present the methodology used to design, construct and verify the first CE test facility built from the ground up following the guidelines of ASTM-E3087.18.
3. Identify a consistent means to quantify the repeatability and reproducibility of CE using experimental data.
4. Identify and minimize factors of the CE test facility and test procedure that influence CE, as well as its repeatability and reproducibility.
5. Identify factors of the rangehood/test configuration that influence CE, as well as its repeatability and reproducibility.
6. Develop a faster and less expensive method for determining a CE consistent with ASTM test results by using an image-based or computational fluid dynamics (CFD) model.
7. Describe how knowledge gathered from this study will support development of a new Home Ventilating Institute (HVI) certification procedure.

CHAPTER II

REVIEW OF RANGEHOOD CAPTURE EFFICIENCY MODELS FROM 2009 – 2019

Overview

A literature review was performed to investigate test methods developed to perform CE testing, and how their respective test methodologies and procedures compare to ASTM-E3087.18 (i.e. CE calculation approach and tracer gas material/emission properties). The literature review revealed that, aside from the test chamber described herein, there are only seven test facilities at six public institutions, with varying levels of sophistication, that have been used to conduct repeated measurements of residential rangehood CE performance. Only five out of the seven controlled test facilities have been built specifically to conduct CE performance testing of domestic rangehoods; while the other two facilities consist of a research house/kitchen that are also used to perform testing on various household technologies. Furthermore, of the seven test facilities reviewed, only one, which is the aforementioned LBNL facility, is used to perform routine CE testing of household, wall-mounted rangehoods by using a known concentration of a tracer gas (Walker, 2016). This literature review also discusses briefly some CE test methodologies from some case studies (i.e. CE determined by field studies of hoods installed in real-world settings), as well as computational fluid dynamics (CFD) and image-based analyses that are relevant or similar to the test methodologies used in ASTM-E3087.18 and described in this dissertation.

Laboratory studies

Laboratory studies performed at LBNL

Aside from the capture efficiency (CE) test chamber presented in this study, there is only one other CE chamber in a public institution, namely at LBNL, that is compliant with ASTM-E3087.18 and used to perform CE testing. The test chamber built and described herein, as well as the ASTM standard, is based on two studies performed by LBNL (Walker, 2016 and Kim, 2017). In these respective LBNL studies, Walker et. al. developed a test facility mimicking a kitchen and analyzed various testing configurations including CO_2 sensor placement, chamber air change requirements and CO_2 sample frequencies to determine a standardized test method for measuring steady-state CE by using a tracer gas (i.e. CO_2) and Equation 1 below.

$$CE = \frac{C_{exhaust} - C_{chamber}}{C_{exhaust} - C_{inlet}} \times 100\% \qquad (1)$$

where $C_{exhaust}$ represents the concentration of tracer gas in the exhaust duct (ppm), $C_{chamber}$ represents the concentration of tracer gas in the simulated kitchen or chamber (ppm) and C_{inlet} represents the concentration of tracer gas at the inlet to the chamber (ppm).

Kim et. al. (2017) modified the above test chamber and expanded the test method to make it more replicable (i.e. consistent design using CO_2 emitters) and to further reduce uncertainty (i.e. modifying chamber inlet and depressurization requirements). Both studies, namely Walker et. al. (2016) and Kim, et. al. (2017) made continued progress towards the development of a standard capture efficiency test method and facility for domestic, wall-mounted rangehoods that is the new ASTM standard as described by Kim et. al. (2018).

The above Walker (2016) study was the first of its kind in that it utilized a controlled concentration of tracer gas to quantify residential rangehood CE in a laboratory setting. Previous studies performed by LBNL on residential, wall-mounted rangehoods characterized CE by measuring the by-product of CO_2 generated when using a gas range to boil water (Singer, 2012 and Delp, 2012). Although Delp and Singer showed that rangehood type/geometry and burner placement can influence CE measurements, neither of the studies utilized a known concentration of CO_2, which is consistent with testing under controlled conditions. Furthermore, Walker emphasizes that the use of a combusting gas is not sustainable for long-term testing due to both safety concerns associated with the large amounts of natural gas required for continuous boiling of water and possible variations in pot sizes that could easily exist among test facilities, thus influencing CE measurements.

The objective of Walker's study was to analyze sensor placements, sampling rates and air changes in order to determine a consistent measurement for CE. Using a test method that would later be incorporated and described in ASTM-E3087.18, Walker reported being able to achieve results that were repeatable within +/- 0.5% CE, as determined by a 1% maximum standard deviation observed for repeated tests, and uncertainties less than 2% after four air changes. Walker's data plotted in Figure 1 shows the relationship between CE and airflow, revealing that CE increases with increasing airflow rates. Walker concluded that rangehood flowrate, geometry and mounting height all have a significant impact on CE performance, which can also be seen in Figure 1. It is important to note that the experimental setup in Walker's study used a CO_2 emitter design and placement were different from that required by ASTM-E3087.18, which is presented later when the test facility designed and constructed during this dissertation study is described.

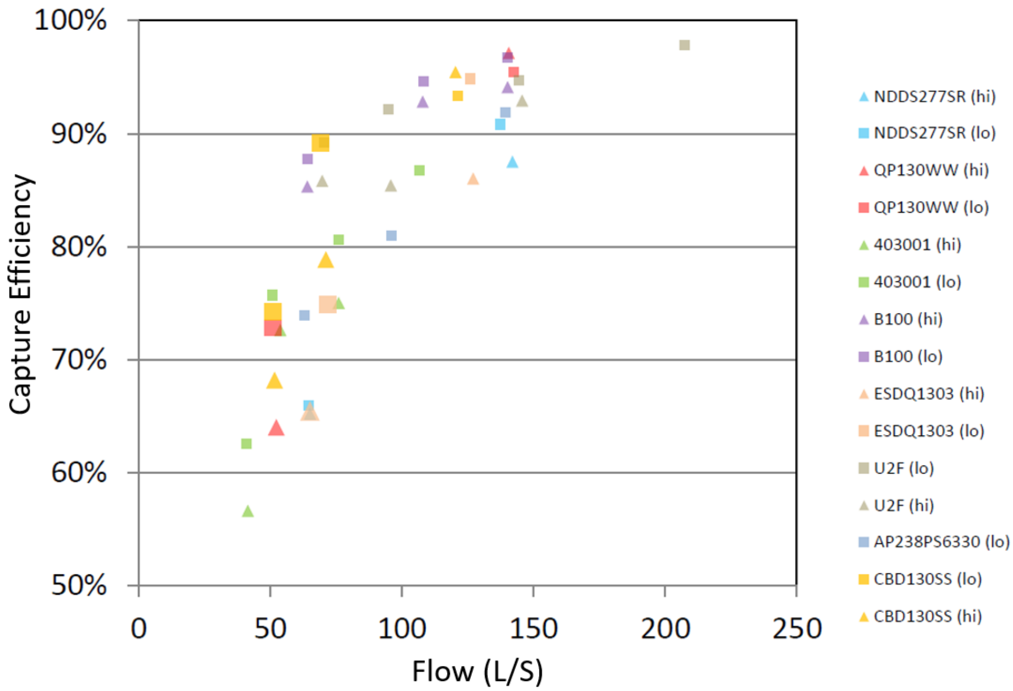


Figure 1: Capture Efficiency vs. airflow rate for eight different rangehoods tested by Walker et. al.

Each color in Figure 1 has two symbols, namely a square and a triangle, for most of the rangehoods tested, with each of these symbols representing a low and high mounting height, respectively. It can be observed that any given rangehood can have a different CE value at the same flowrate due to its varying geometry upstream of the rangehood. For example, Figure 1 shows that in nearly all cases the low mounting height produces a higher CE compared to that of the higher mounting heights. Additionally, the enlarged symbols in Figure 1 represent those units that satisfy ASHRAE 62.2 minimum requirements for both airflow and sound. It should be noted that there would have been even more of these enlarged symbols if not for the fact that many units did not meet ASHRAE 62.2 requirements for sound at high flowrates.

Kim et. al. (Kim, 2017) elaborated on Walker's study by using the same test chamber that was used in the development of the ASTM standard, but with only one sensor to measure the chamber CO2 concentration, which Walker showed causes a 1% CE variation in most of the cases analyzed. Additionally, Kim et. al. modified the chamber inlet to reduce the effects of make-up air disturbing flow patterns near the chamber sensor and in the gas plume above the cook-top. Finally, Kim et. al. developed new CO2 emitters that were intended to be more easily replicable and are identical to those specified by ASTM-E3087.18, although it is not clear if the spacing in their study conforms to ASTM-E3087.18 as the emitters were set on an electric range with fixed burner positions. It should be noted that the ASTM specifies a distance of 500mm (20in.) from the back wall and a distance of 100 – 300mm (4 – 12in.) from the centerline of the rangehood depending on rangehood width. The electric stove in Walker's and Kim's studies used burner spacings of 280 mm for the back burner and 500 mm for the front burner; however, the lateral spacing is not clearly defined, making it impossible to determine a conformity with the ASTM standard.

Kim's study tested two different rangehoods to observe any biases which may exist between the test set-up used in their study versus that used by Walker et. al., by comparing the following parameters: old inlet vs. new inlet, old emitters vs. new emitters, position of emitters (one back and one front vs. two in the front) and high vs. low mounting height. For the two rangehoods tested, the low-flow rangehood was tested at two speeds (high and low) and the high-flow rangehood was only tested at the high speed. In total, Kim analyzed over 70 unique cases for these two rangehoods (i.e. varying emitter type, inlet type, burner placement, airflow rate, etc.) with the results for the new inlet, new emitter configuration being presented in Figure 2. It should be noted that the square and circle symbols in Figure 2 represent the two range hood models tested by Kim. Additionally, the larger symbols in Figure 2 represent the higher mounting height and the smaller symbols represent the lower mounting height.

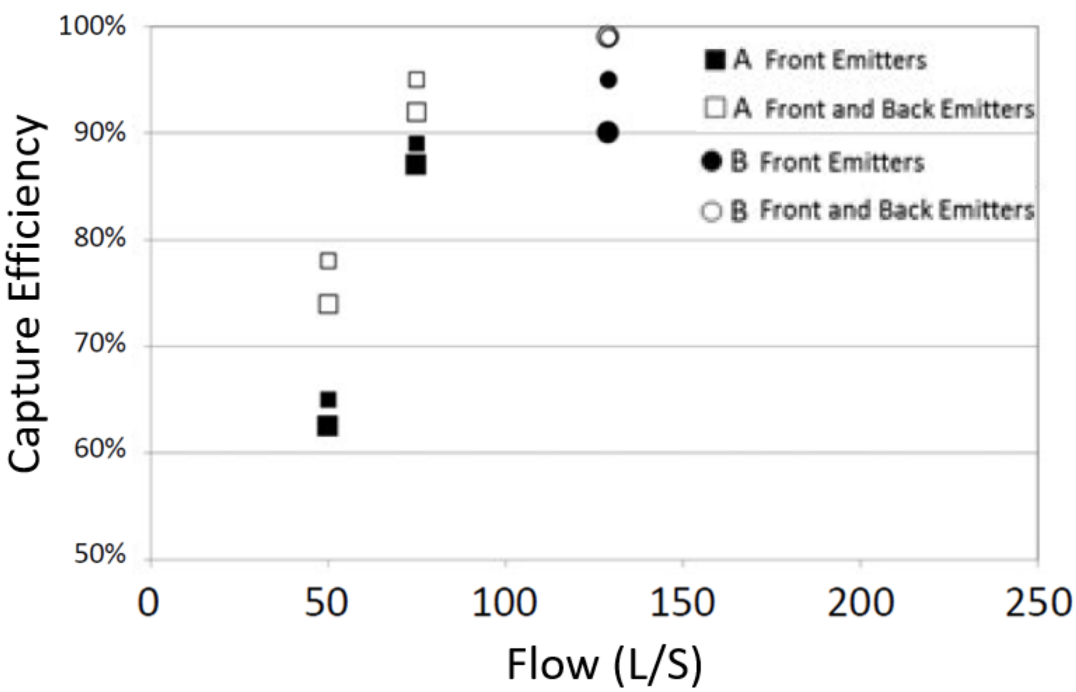


Figure 2: Capture Efficiency vs. airflow rate for the two rangehoods tested by Kim et. al.

Furthermore, the new emitters were ultimately selected due to their ability to be easily replicated with minimum variations among research labs. As shown in Figure 2, the front burner placement was generally found to result in a lower CE and a larger variability for varying flow rates (a range of 63%–95% CE) compared to one front and one back burner (a range of 74% – 99% CE). The larger variation in CE when using front burners led the ASTM task group to decide on this placement of the burners (i.e. front burners) to allow for a larger range of CE performances for rangehoods tested. Even though the old and new inlets are not compared in Figure 2, other comparisons resulted in the new inlet being selected as it reduced variations in CE by reducing the velocity of the air jet coming into the chamber, which could produce disturbing flow patterns that cause variations in CO2 and CE measurements. It is also important to note, that similar to Walker et. al. (Walker, 2016), range hood CE varies with mounting height, with the higher mounting heights showing a decrease in CE.

Both Walker et. al. (Walker, 2016) and Kim et. al. (Kim, 2017) observed that a consistent CE, defined by a standard deviation of +/- 1.5% CE between consecutive measurements, can be determined by using 10-minute interval periods after the chamber has undergone 4 air changes due to the temporal error associated with CE measurements (i.e. fluctuations in the CO_2 measurements). Based on these results, ASTME-3087.18 specifies a 10-minute interval period after 4 air changes. However, based on rangehood design/configuration, both Kim et. al. (Kim, 2017) and Walker et. al. (Walker, 2016) observed that some rangehoods require as many as eight air changes to achieve conditions for a steady-state CE measurement.

As noted, there are no test facilities, besides the LBNL facility and the one presented herein, that are capable of measuring CE performances of a wide variety of wall-mounted, domestic rangehoods under controlled conditions following ASTM-E3087.18. However, other facilities exist that have been used in the past to investigate and quantify the effects of rangehood usage on indoor air quality (IAQ), most of which are discussed in the next sub-section. In most of these cases, the CE was investigated by observing how rangehood operation influences IAQ rather than using a standardized method for quantifying CE.

Aside from the wall-mounted, rangehood test chamber at LBNL, which was described previously herein, there is a second test chamber at LBNL that also utilizes known concentrations of tracer gas to measure the CE performance of domestic rangehoods (Clark, 2018). However, this second chamber is primarily used to test island and down-draft rangehoods, which are mounted over (or level with) an island countertop without any adjacent walls or cabinetry. Clark et. al. performed CE testing by using methods similar to ASTM-E3087.18 in terms of CO2 sensor placement and the equation for calculating CE; however, research is still ongoing concerning optimum burner power/temperature and determining steady-state conditions at lower flow rates. In this regard, the test procedure is still being established with the results from Clark’s study being used to directly support development of another ASTM standard for CE testing of island rangehoods.

Other laboratory studies relevant to ASTM-E3087.18

Some other laboratory studies were performed that investigated the CE performance of domestic wall-mounted rangehoods, however, most of these studies deviate significantly from the CE test procedure. Specifically, none of the test procedures use a controlled injection rate of tracer-gas for quantifying CO_2 and some of these studies were performed in simulated houses or facilities containing multiple rooms, as opposed to an isolated test chamber as prescribed by ASTM-E3087.18. One study involving the construction of a test chamber for quantifying rangehood CE was done by Zhou et. al. (2019) in which a facility was designed for testing push-pull ventilation systems in a kitchen. A push-pull ventilation system consists of an air curtain (AC) around the perimeter of the cook-top, which forces air upwards and into the range-hood. In their study, one rangehood was installed at a fixed mounting height and operated at three different speeds. Additionally, the air curtain was set to three different speeds and an external window was either opened or closed during CE testing. Zhou's test facility did not utilize the injection of a tracer gas at a controlled rate, however the study used the same formula for CE derived by Walker (2016) and used in the ASTM test standard (ASTM, 2018), which requires the measurement of CO_2 concentrations at three points in the test facility. Of specific note, Zhou et. al. used 30 mL of soybean oil to fry 100g of cowpeas under a regulated power of 836 W and then measured CO_2 emissions at the three points in the test facility. Zhou (2019) mentions that the CO_2 concentration measurements were taken after the concentrations reached steady-state, although it is not clear how this action relates to the 4 air changes specified by ASTM. It is important to note that this push-pull ventilation system is not a common feature of household kitchens; nevertheless, Zhou (2019) found that increasing airflow through the rangehood can increase CE, but after increasing air-curtain airflow rates above a certain value, then the rangehood CE is decreased.

Another study that did not involve the injection of a known concentration of CO_2 was performed by Dobin et. al. (2018) at the Canadian Center for Housing Technology (CCHT) where wall-mounted rangehood CE performances were analyzed in a controlled facility designed for testing household appliances. The research facilities are identical two-story, four-bedroom, three-bathroom detached houses with a floor area of 2260 ft^2. However, the houses were not built to perform CE testing of rangehoods, but rather to aid in the development of general housing technologies and their integration into the market place. The CCHT study involved analyzing CE performances for three different fans at six total speeds (one at 3 speeds, one at 2 speeds and one at a single-speed). It is not clear whether all of the fans were installed at the same mounting height or whether the CCHT even has the capability for adjusting rangehood mounting heights. Additionally, there is no explicit CE formula used to quantify range hood CE, but rather an asymptotic concentration corresponding to the equilibrium concentration between the pollutant generation and removal rate. The CCHT test procedure involved frying and boiling different food items on a gas stove with the rangehood running, while observing the change in particulate matter (PM) during testing. After cooking had concluded, two rangehood operating conditions were analyzed, namely off and on, which represented either leaving the rangehood on for 3 hours after cooking or immediately shutting it off.

Conclusions were then drawn as to the benefits of using a rangehood during cooking by observing the decay rate of contaminants in the home and the peak contaminant level under the different rangehood operating conditions. Dobin et. al concluded that increasing the flow rate by 100 cfm has the same effect as leaving the hood running for 15 minutes after cooking, which suggests that one can partially compensate for low flowrate rangehoods by continuing to run them after the cooking is finished.

Poon et. al. (2016) designed a rangehood test facility that was comprised of two separate zones, with one zone (cooking zone) simulating the kitchen and the other zone (non-cooking zone) representing other parts of the house. The focus of their study was to investigate how rangehood operations influence contaminant generation in the kitchen, as well as the dispersion of cooking contaminants to non-cooking areas throughout the home. Poon et. al. investigated the distribution of particles in the two zones under four different range-hood operating conditions at one fixed height, by boiling a fixed amount of water and then using a condensation particle counter to analyze the contaminant levels in the space. The four rangehood operating conditions were: 1) off-off, 2) off-on, 3) on-off, 4) on-on, where the first and second sequence represent rangehood operations during cooking and after cooking, respectively. Poon et. al. did not perform explicit CE calculations, but rather observed how the concentrations in the two zones varied due to the various rangehood operating conditions (i.e. ratio of total concentration released to the two zones). Poon et. al. concluded that although there is cross-contamination between zones due to cooking and rangehood operations, the rangehood airflow has a dominant influence on the distribution of condensation in the two zones.

Another test chamber found in the literature review is one that consists of a simulated kitchen with different diffuse ceilings for varying rangehood airflow rates in order to simulate a controlled inlet (O'Leary, 2019). Located at the Netherlands Organisation for Applied Scientific Research (TNO), this test chamber was not specifically designed to perform range hood CE testing but rather a climatized room in which a kitchen was built. O'Leary et. al. used the TNO test facility in order to observe the effects of rangehood use on cooking several different meals by measuring variations in particulate matter (PM) associated with frying/boiling of food items or gas stove emissions, which also means that this study did not utilize a known concentration of tracer gas as specified by the ASTM. In addition to not being performed in accordance with ASTM-E3087.18, none of these studies were performed with the intent of developing a consistent CE test method, but rather to observe how rangehood usage effects IAQ during cooking. In fact, there is not mention of an explicit expression for CE, but rather comparison of various contaminant emission rates into the kitchen based on PM measurements. Furthermore, even though rangehoods were operated under high and low air flowrates, to observe the effect on PM emission to the test space, the focus of this study was limited to investigating the effect of cooking different foods on PM emission rates.

Some other studies have been performed to investigate the efficiency of fume hoods that minimize heat/contaminants generated in industrial/laboratory processes (Devienne, 2009), as well as CE studies of commercial-grade kitchen rangehoods (Li, 2014). However, these studies are not presented since wall mounted, residential rangehoods are the focus of this dissertation. Furthermore, the test procedures described in these other studies are not applicable to domestic rangehoods due to variations in size (i.e. kitchen size vs. manufacturing plant) and the complexity of commercial/manufacturing exhaust systems. Furthermore, most of the test methods used in these other studies do not apply to the testing of domestic rangehoods as they utilize much higher surface temperatures (i.e. those associated with soldering/machining) as well as higher airflow rates and larger test facilities (i.e. more ventilation space to accommodate equipment and higher ceilings to accommodate exhaust systems).

Case studies

Several past studies have been conducted to characterize CE performance of domestic rangehoods in the real-world setting of an actual kitchen in a residence as opposed to operating in a controlled test chamber designed specifically for CE testing (Singer, 2012, Delp, 2012 and Rim, 2012). A major weakness of these studies is that they did not utilize a controlled test facility that could be used for repeat quantification of CE performances for a wide range of domestic rangehoods, nor did they utilize a known concentration of tracer gas as specified by ASTM-E3078.18. For these reasons, the study results are not discussed herein, but rather listed in the references section.

It is important to note that in addition to not using known concentrations of a tracer-gas, the aforementioned studies did not emphasize the use of a consistent/repeatable mounting heights, or lack thereof, nor a specified cook-top temperature. Additionally, all case studies presented in the references used a different formula for calculating CE that differs from that used by Walker et. al. (2016) and Kim et. al. (2017) and promulgated by ASTM-E3087.18. Nevertheless, all studies varied airflow rates through the rangehood and the burner positions, with the conclusion being that CE increases with increasing airflow rates and with the usage of back burners.

Image-based models

In reviewing image-based models from 2009 – 2019, it was found that only one study utilized an image-based model for determining the capture efficiency (CE) of a household kitchen range hood (Xu, 2017). The test procedure modeled resembles that of ASTM-E3087.18 in that two identical tracer gas emitters are used to inject a constant mass flow rate of CO_2 and CO. However, the intent of the study is not to provide a quantifiable CE metric, but rather to investigate the temperature and contaminant distribution in an open-kitchen environment (e.g. kitchen connected to living space) with/without windows in the kitchen/living space. In fact, there is not CE metric performed in the study performed by Xu et. al., but rather only temperature and contaminant distributions in the two living spaces.

It should also be noted that one other study prior to 2009 (Li, 2001) uses an experimental test procedure to verify an image-based model for range hood CE that was developed even earlier (Delsante, 1996). The image-based model performed by Delsante et. al. does report a CE metric, but it is different from that described in the recently developed ASTM standard. Additionally, both of these studies use a single tracer-gas emitter/heat source, which is much different than that specified in ASTM-E3087.18. For these reasons, these studies are not discussed in full detail but are listed in the References section of this dissertation.

CHAPTER III

ASTM TEST METHOD FOR CAPTURE EFFICIENCY

Overview of ASTM test method

The ASTM test method studied in this dissertation is the first of its kind to utilize a known and controlled concentration of a tracer-gas in order to quantify the capture efficiency (CE) of domestic, wall-mounted rangehoods. Aside from the test facility described herein, there are no other non-proprietary test facilities that are capable of performing testing following guidelines promulgated by a standard recently implemented, namely ASTM-E3087.18: Standard Test Method for Measuring Capture Efficiency of Domestic Range hoods. However, a non-proprietary operating facility with similar characteristics was developed earlier at Lawrence Berkeley National Laboratory (LBNL), and it was used to perform testing in support of developing ASTM-E3087.18, which quantifies rangehood CE by using a tracer-gas to simulate cooking contaminants.

ASTM capture efficiency test methods

Test procedure

The new ASTM test procedure, ASTM-E3087.18, injects a known concentration of tracer-gas into a simulated test kitchen in order to determine the capture efficiency (CE) of a rangehood unit under test. The tracer-gas is intended to simulate contaminants created while cooking and is injected into the test chamber using machined emitter-plates with dimensions developed by LBNL and specified by the ASTM. By measuring the concentration of tracer-gas at various points in the test chamber, namely the inlet, exhaust and chamber interior, the CE can be determined by calculating the ratio of tracer-gas concentration in the exhaust to the tracer-gas concentration in the chamber (i.e. that portion of cooking contaminants exhausted out of the residence as opposed to those which enter the residence.)

ASTM-E3087.18, which was developed by LBNL as described by Kim et. al (2018) utilizes measurements of a tracer gas, namely CO2, at various points in a simulated kitchen to determine capture efficiency (CE). By using measurements of CO_2 concentrations at the chamber inlet (C_{inlet}), inside the chamber ($C_{chamber}$) and the chamber exhaust ($C_{exhaust}$), the capture efficiency (CE) can be calculated by using Equation 1, which was introduced earlier and is shown below for reference:

$$CE = \frac{C_{exhaust} - C_{chamber}}{C_{exhaust} - C_{inlet}} \times 100\% \tag{1}$$

The ASTM test method specifies that the chamber must undergo four air changes prior to taking measurements of CO_2 concentration, with 'steady-state time' required to undergo 4 air changes being defined in Equation 2 below.

$$T_{SS} = 4\frac{Q_{hood}}{V_{chamber}} \tag{2}$$

Where, T_{SS} is the 'steady-state time' (min.), Q_{hood} is the air flow rate through the rangehood (cfm), $V_{chamber}$ is the volume of the chamber (ft^3) and four (4) is the factor considering four air changes. After the chamber undergoes four air-changes a minimum of ten measurements are required for each CO_2 concentration (C_{inlet}, $C_{chamber}$, $C_{exhaust}$), before the values are averaged to calculate one CE, as shown in Equation 1. It is also important to note that ASTM-E3087.18 specifies that for 10 sets of measurements for each of the parameter values (i.e. C_exhaust, C_chamber, etc.) all values shall be measured before taking the second measurement of any one value and so forth, up to 10 sets.

Test facility

Figure 3 is an illustration of a CE test facility, with the locations of the three CO_2 measuring points identified in Equation 1 and used to determine CE. The seven key components that comprise the test facility are also shown in Figure 3, with each being described and discussed in the next section. To be specific, the seven major components of the test facility, which are numbered 1 through 7 in Figure 3, are the test chamber, rangehood (unit under test), cook-top, CO_2 emitter system, chamber inlet, chamber exhaust, and CO_2 detection system. Not pictured in Figure 3 are the associated instrumentation and data acquisition station. A detailed description of each of the seven components is provided in the next Chapter.

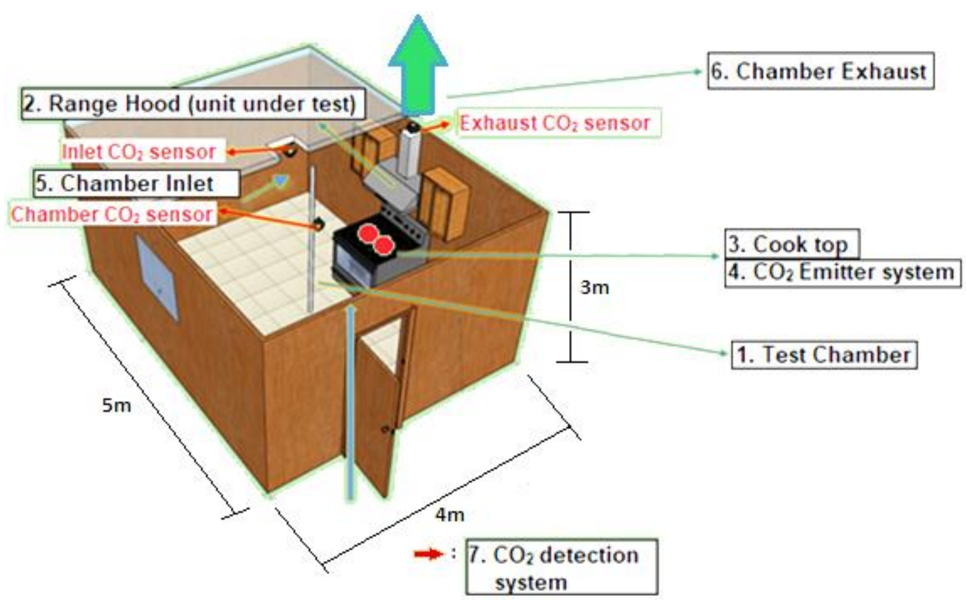


Figure 3: Test Chamber used for capture efficiency testing with associated sub-components

The following section describes the ASTM specifications and requirements that were adhered to while designing and building the seven key components that comprise the test facility.

ASTM capture efficiency test facility requirements

Test chamber

The ASTM test method specifies minimum size requirements of 2.5 m by 3.5 m with the rangehood being mounted against the longer of the two walls. The ceiling height of the test chamber is specified to be between 1.1 m and 1.2 m as specified by ASTM-E3087.17.

Air tightness of the chamber shall be tested in accordance with the ASTM-E3087.17 test method by imposing a gauge pressure of 50 Pa and measuring the airflow required to maintain this pressure. The chamber of volume, V, shall have less than 2.5 air changes per hour as specified by the ASTM and shown below in Equation 3:

$$Air\ Changes\ per\ Hour = \frac{3.6\ Q_{50}}{V} \tag{3}$$

Q_{50}: flow rate required to maintain 50 Pa (L/s)

V: Volume of the chamber (m^3)

3.6: Conversion ratio ($m^3 \rightarrow$ L and sec. $\rightarrow$ hr.)

Chamber inlet

The inlet shall be constructed so that incoming air does not directly impinge on the range hood or tracer gas emitters. There shall be at least a 1 m (3 ft.) separation between an air inlet and the range hood being tested and/or the cooktop. Additionally, the inlet shall be fitted with a diffuser plate that diverts inlet air away from the unit under test. Figure 3 presents an example image of the inlet, airflow redistribution systems.

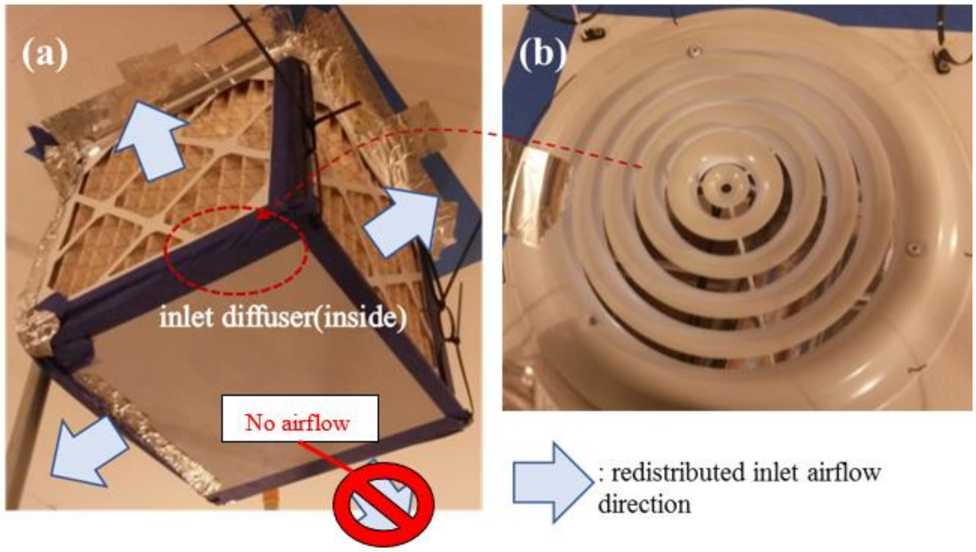


Figure 4: Images of (a) the airflow redistributions and (b) air inlet diffuser from the LBNL setup.

The ASTM specifies that the inlet(s) shall be sized such that the average inlet air velocity is less than 0.5 m/s. Additionally, a sufficient number of inlets shall be used such that when the range hood under test is turned on, the chamber does not depressurize by more than 5 Pa.

Chamber exhaust

The chamber exhaust system shall be used to connect the outlet of the range hood to the outdoors, or an environment isolated from the test chamber. The exhaust (and inlet) shall be sized such that the chamber is not depressurized by more than 5 Pa during operation of the test unit.

The exhaust system shall include a flowmeter with an accuracy of +/- 2.5 L/s (5.3 cfm) or 5% of measured flow (whichever is greater) to measure the range hood exhaust air flow (Q_{hood}). An auxiliary fan and damper will be connected in line with the range hood exhaust so that Q_{hood} can be adjusted to specified operating points, e.g., external static pressures.

Additionally, per the ASTM standard, the exhaust tracer gas concentration ($C_{exhaust}$) shall be measured in the range hood exhaust ducting at a point at least 10 duct diameters downstream of the connection to the range. Concentration measurement shall have five sample points across the exhaust duct cross-section

Finally, the exhaust system shall also undergo a separate leakage test to ensure accurate flow readings and CO_2 concentration measurements. A fan and flowmeter (with an accuracy of 0.25 L/s or 5% of reading) shall be temporarily attached to one end of the exhaust duct while the other end is blocked. The fan shall then be used to pressurize the exhaust duct to 25 Pa and the flow required to achieve this pressure will be recorded. The maximum air leakage from the exhaust system shall be less than 2.5 L/s (5.3 cfm) at a test pressure of 25 Pa

Rangehood under Test

The ASTM test standards is written for rangehoods as large as 0.9 m (36 in.) and airflows up to 200 L/s (424 cfm). Additionally, ASTM-E3087.18 does not specify a mounting height for the range As mentioned previously, the ASTM test method specifies mounting the rangehood against the longest wall of the chamber, though it does not specify the degree of flushness. Therefore, proper measures will be taken to ensure that the range hood can be mounted at various heights, and be placed flush with the back wall/adjacent cabinets while under test

Cook-top

The ASTM standard specifies that the upper surface of the cooktop shall have a height of 0.9 m (36 in.) from the floor and have a depth of 0.65 m (26 in.) from the back wall. Also, counter tops shall extend a minimum of 0.5 m (20 in.) on each side of the range hood (i.e. a minimum width of 76 in. for the 36 in. (max) range hood width). Additionally, ASTM-E3087.17 specifies varying the locations of the heating elements depending on range hood size, thus the cook-top will be comprised of a workbench that conforms to the ASTM standard size requirements and three portable electric burners.

CO_2 emitter system

The ASTM requires a specific design of CO_2 emitters to be used for ASTM capture efficiency testing in accordance with ASTM-E3087.18. Figure 5 presents the dimensions of perforated CO_2 emitter surfaces developed by LBNL and promulgated through ASTM-E3087.18.

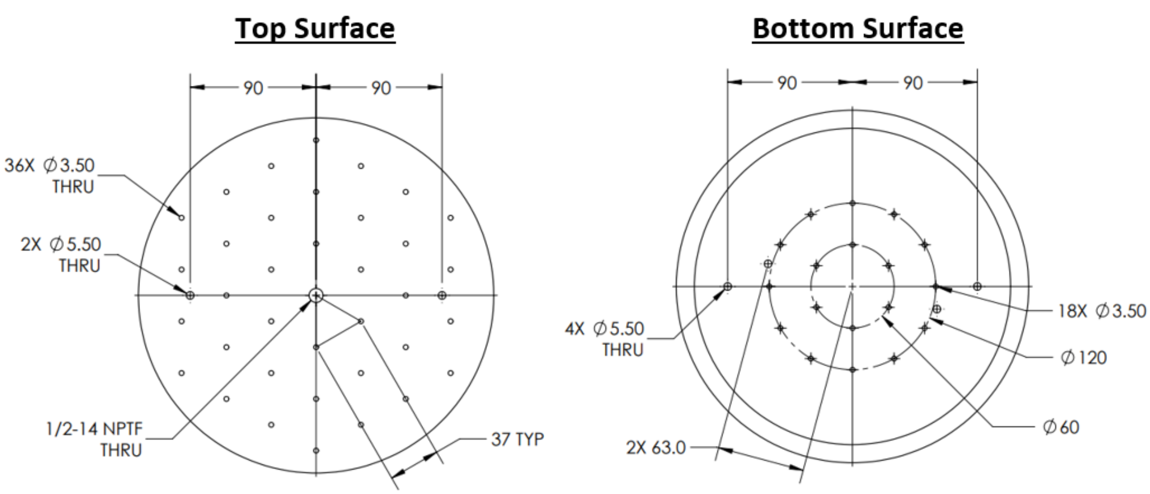


Figure 5: Sketch and dimensions (in mm.) of the CO2 emitter for the upper (left) and lower (right) surfaces.

Per the ASTM standard, the combined volumetric flow from both the CO_2 emitters shall not exceed 0.5% of the volumetric flow through the range hood. Additionally, the tracer-gas injection rate shall be controlled to within +/- 1% by using a mass flow controller.

<u>CO_2 detection system</u>

Previous studies (Walker, 2016 and Kim, 2017) showed that the maximum CO_2 reading in the exhaust, at the injection rate specified, typically does not exceed 3000 ppm. As a conservative estimate, the group assumed a range between 0-5000 ppm for CO_2 concentrations would be expected during testing.

It should be noted that three CO_2 concentration measurement points, namely inlet, chamber, and range hood exhaust, are necessary to determine the capture efficiency (CE), which is defined as follows:

$$CE = \frac{C_{exhaust} - C_{chamber}}{C_{exhaust} - C_{inlet}} \quad (1)$$

$C_{exhaust}$: CO_2 concentration in the range hood exhaust (ppm or kmol/m^3)

$C_{chamber}$: CO_2 concentration in the test chamber (ppm or kmol/m^3)

C_{inlet}: CO_2 concentration at the air inlet of the chamber (ppm or kmol/m^3)

ASTM states that a gas analyzer grade CO_2 sensor is utilized with an accuracy less than 1% of the difference between $C_{exhaust}$ and $C_{ambient}$. It was assumed that the minimum difference between $C_{exhaust}$ and $C_{ambient}$ would be 1000 ppm. Thus, a sensor with an accuracy of ±10 ppm is enough. Additionally, the ASTM standard states that all tracer gas concentrations shall be measured by using the same measurement device.

ASTM Definition of Uncertainty

The newly developed ASTM test method presents a procedure for determining the uncertainty in CE (δ), which is mainly based on the variations in CO_2 concentrations between the sets of 10-measurements. The ASTM explicitly states that the new teste method, ASTM-E3087.18 has not yet been subjected to long-term or standardized precision and bias (uncertainty) testing. Additionally, ASTM states that the uncertainty calculation is still considered preliminary

The preliminary precision and bias procedure outlined in ASTM-E3087.18 considers the variations in CO_2 concentration (i.e. standard error) as well as the typical variations in CO2 (i.e. temporal error) that one would expect to encounter during testing, due to the nature of the flow at the various testing points. That is, the variation that one might expect to see in an exhaust CO2 reading is likely going to be much higher due to the higher volumetric airflow rates in the exhaust.

The error in individual concentrations is calculated as follows:

$$\delta(C_{Exhaust}) = \sqrt{(\delta_P(C_{Exhaust}))^2 + (\delta_{SE}(C_{Exhaust}))^2} \quad (4)$$

$$\delta(C_{Chamber}) = \sqrt{(\delta_P(C_{Exhaust}))^2 + (\delta_{SE}(C_{Exhaust}))^2} \quad (5)$$

$$\delta(C_{Inlet}) = \sqrt{(\delta_P(C_{Exhaust}))^2 + (\delta_{SE}(C_{Exhaust}))^2} \quad (6)$$

Where, δ_P is the precision, or temporal, error of the measurement (δp(C_Inlet) = 0 %, δp(C_Exhaust) = 0 %, δp(C_Chamber) = 1.25%) and δ_{SE} is the standard error between the ten CO_2 measurements.

The uncertainty in CE is then calculated as follows, with a sample calculation also being presented.:

$$\delta CE = CE\left[\sqrt{\frac{(\delta(C_{Exhaust}))^2 + (\delta(C_{Chamber}))^2}{(C_{Exhaust} - C_{Chamber})^2} + \frac{(\delta(C_{Exhaust}))^2 + (\delta(C_{Inlet}))^2}{(C_{Exhaust} - C_{Inlet})^2}}\right] \quad (7)$$

Sample calculation:

$$C_{Exhaust} = 2500, \delta_P(C_{Exhaust}) = 0, \delta_{SE}(C_{Exhaust}) = 25$$

$$C_{Inlet} = 500, \delta_P(C_{Inlet}) = 0, \delta_{SE}(C_{Inlet}) = 5$$

$$C_{Chamber} = 1000, \delta_P(C_{Chamber}) = 12.5, \delta_{SE}(C_{Chamber}) = 2$$

$$CE = \frac{2500 - 1000}{2500 - 500} = 0.75 = 75\ \%CE$$

$$\delta(C_{Exhaust}) = \sqrt{(\delta_P(C_{Exhaust}))^2 + (\delta_{SE}(C_{Exhaust}))^2} = \sqrt{25^2} = 25$$

$$\delta(C_{Chamber}) = \sqrt{(\delta_P(C_{Exhaust}))^2 + (\delta_{SE}(C_{Exhaust}))^2} = \sqrt{12.5^2 + 2^2} = 12.6$$

$$\delta(C_{Inlet}) = \sqrt{(\delta_P(C_{Exhaust}))^2 + (\delta_{SE}(C_{Exhaust}))^2} = \sqrt{5^2} = 5$$

$$\delta CE = CE\left[\sqrt{\frac{\left(\delta(C_{Exhaust})\right)^2 + \left(\delta(C_{Chamber})\right)^2}{(C_{Exhaust} - C_{Chamber})^2} + \frac{\left(\delta(C_{Exhaust})\right)^2 + \left(\delta(C_{Inlet})\right)^2}{(C_{Exhaust} - C_{Inlet})^2}}\right]$$

$$= 75\left[\sqrt{\frac{(25)^2 + (12.6)^2}{(1500)^2} + \frac{(25)^2 + (5)^2}{(2000)^2}}\right] = 75[0.023] = 1.7\ \%CE$$

ASTM Test Method Shortcomings

Repeatability Metric

A large portion of this dissertation is the contribution to a new Home Ventilating Institute (HVI) certification program for quantifying the capture efficiency (CE) performance of domestic wall-mounted rangehoods and ultimately advertising this CE ‘number’ to manufacturers and consumers as discussed in Chapter VIII. However, in order for a CE ‘number’ to be advertised to a manufacturer/consumer two things must also exist in support of this CE ‘number’. First, the CE-value (% CE) must be specified with a specific tolerance (i.e. degree of variability). That is, a CE-value is not always going to be 78.2% exactly, but will have some degree of variability. Second, the CE-value must also be able to be repeatable and reproducible when performed numerous times and between various labs.

Previous LBNL studies mainly emphasize the repeated CE-value during a specific test to achieve steady-state (Walker, 2016) and comparing CO_2 emitters and inlets (Kim, 2017), however, very little emphasis is given to the mounting/dismounting of rangehood fans and the degree of repeatability/reproducibility for testing performed using newly-assembled ductwork or even in a different lab. Specifically, LBNL mentions that some of their tests required more than 4 air-changes, and closer analysis of their data shows that about 15 – 20% did require more than 4 air-changes (Walker, 2016). On that same note, LBNL emphasizes that depending on the CO_2 sampling rate and sampling window, one may see some measurements being closer together or further apart (Walker, 2016). Additionally, LBNL emphasizes in the study describing the development of the ASTM standard, that an inter-laboratory comparison would be highly valuable to investigating the effects on CE performance and consistency, specifically with regards to various chamber shapes/sizes (Kim, 2018).

Vagueness of rangehood installation requirements

The ASTM standard was originally released in 2017 before being revised within the first year to includes some changes with regards to the rangehood installation and test methods. The original 2017 version specified a minimum mounting height for the range hood of 0.5m (19.7in) from the cook-top. Additionally, it is not clear whether the mounting height should be measured from the surface of the counter-top or from the top of the CO_2 emitters, which sit atop portable electric burners at a height of 7in. as discussed in the next chapter. The 2018 version of the ASTM test method removed the test height requirement based on observation from this study, but it is still important to investigate the effects of mounting height from a rangehood certification perspective. That is, a test height should be specified that gives an accurate representation of the real-world CE, while also being able to achieve a certain degree of repeatability.

On a similar note, the 2017 version of the ASTM standard had specified a cook-top surface temperature of 200C, and in fact it seems all previous LBNL studies were performed at 200C. The 2018 version of the ASTM standard revised the cook-top temperature to 160C, however it is not clear if a thorough analysis was performed to investigate the effects of changing the surface temperature and whether or not 160C is the optimum surface temperature to give an accurate representation of real-world CE (i.e. reflecting real-world cooking scenarios, while also considering repeatability performance). In that regard, it is important that the effects of surface temperature and mounting height be thoroughly investigated to identify the ideal configuration for certification testing and for thoroughly understanding rangehood CE performance.

Live monitoring of capture efficiency

The ASTM standard as it is currently written, specifies the use of one CO_2 sensor for measuring all three concentrations ($C_{exhaust}$, $C_{chamber}$ and C_{inlet}) used to calculate

CE. The reasoning for using one sensor is that the same precision error in a CO2 reading is subtracted from another CO2 reading and then divided as shown in Equation 1, which was introduced earlier but is shown again below (Walker, 2016).

$$CE = \frac{C_{exhaust} - C_{chamber}}{C_{exhaust} - C_{inlet}} \tag{1}$$

LBNL suggests that using multiple sensors may cause more propagation of error and thus lead to an inaccurate CE measurement. However, it is important to note that using multiple sensors gives the user capability to monitor live CE, and thus possibly reducing test times as well as giving more insight to increasing/decreasing trends in CE and steady-state time. in CE trend. LBNL suggests that by utilizing more than one sensor, one may be able to get quicker measurements of CE at the expense of reduced accuracy (Kim, 2018). In that regard, a portion of this dissertation is to investigate the effects of utilizing multiple CO2 sensors on CE and CE repeatability/reproducibility as opposed to using one sensor as specified by ASTM-E3087.18.

Terminology used to address ASTM shortcomings

Repeatability of capture efficiency

It is expected that if CE tests are performed numerous times on a specific range hood then the results will show some slight deviations in CE values due to variations in flow patterns (i.e. CO_2 mixing with air, varying emitter temperatures, etc.) as well as details in the test setup (i.e. emitter placement within ASTM prescribed tolerances, test chamber temperature, pressure in CO_2 tank, etc.). The CE repeatability (ΔCE) is intended to quantify the expected variation between CE tests that are performed multiple times by using the exact same test conditions (i.e. mounting height, burner placement, flexible duct-segment, etc.) as opposed to the CE reproducibility, which is described in the next section and involves variations between CE tests performed when dismounting and re-mounting a range hood.

In this study, the CE repeatability for all cases was determined by calculating the absolute difference, ΔCE, between consecutive tests that were run prior to dismounting (i.e. the difference between Test 1 and Test 2) as shown in Equation 8.

$$\Delta CE = |\mathrm{CE}_1 - \mathrm{CE}_2| \tag{8}$$

CE_1 = CE corresponding to Test 1

CE_2 = CE corresponding to Test 2

ΔCE = Absolute difference between repeat CE tests

Reproducibility of capture efficiency

Unlike the CE repeatability metric (ΔCE) that describes the expected variation between CE tests performed back-to-back without any dismounting/re-mounting, the CE reproducibility is intended to describe the expected variation of CE results for tests performed at a separate instance of time. That is, if a range hood is CE tested and then retested at another instance in the future, then the type of deviation that one might expect to encounter represents reproducibility.

In this study, The CE reproducibility was determined in two different ways following two different metrics, namely α and β. First, the average of Test 1 and Test 2 was calculated to yield an average CE for these two tests denoted as 'CE_avg'. Next, the difference between CE_avg and the CE corresponding to Test 3, which was performed after remounting, was calculated to determine the first metric of reproducibility, α, as follows.

$$\alpha = \left|\frac{|CE_1 - CE_2|}{2} - CE_3\right| = \left|\mathrm{CE_{avg}} - \mathrm{CE_3}\ \right| \tag{9}$$

CE_1 = CE corresponding to Test 1

CE_2 = CE corresponding to Test 2

CE_3 = CE corresponding to Test 3

CE_{avg} = Average of CE_1 and CE_2

α = Metric quantifying reproducibility of tests performed at different instances

The second metric for reproducibility (β) was calculated by observing the maximum discrepancy between reproducible CE tests (i.e. tests that were run with a dismount and remount in between). Specifically, the difference between CE1 and CE3 was compared to the difference between CE2 and CE3 to determine which of the two calculations resulted in a higher variation in CE. Equation 10 shows a breakdown of how the second reproducibility criteria, β, was determined.

$$\beta = \max(|\mathrm{CE_1} - \mathrm{CE_3}|, |\mathrm{CE_2} - \mathrm{CE_3}|) \tag{10}$$

CE_1 = CE corresponding to Test 1

CE_2 = CE corresponding to Test 2

CE_3 = CE corresponding to Test 3

β = Metric quantifying reproducibility of tests performed at different instances.

Variability between multiple tests

To quantify the degree of variability encountered for a specific test set-up/configuration, the coefficient of variation was measured for same scenario tests that were performed more than once and typically at least three times. Based on previous studies, CE values can vary from 49%CE to 93%CE for different cases. Therefore, a measured maximum variation of 4%CE between repeated/reproduced tests for one case may hold significantly more weight than for another case. In that regard, another means to determine the experimentally measured CE variability for tests performed numerous times under specific test conditions is required. In order to quantify a normalized and uniform measurement for CE variation between repeated tests in this study, the coefficient of variation (ε) was calculated for all three tests (i.e. Test 1, Test 2 and Test 3) as shown in Equation 11.

$$\varepsilon = \frac{\sigma}{\mu} \tag{11}$$

σ = standard deviation between three CE tests (i.e. Test 1, Test 2 and Test 3)

μ = average of three CE tests (i.e. Test 1, Test 2 and Test 3)

ε = Coefficienct of variation showing overall variability between tests

By using *ε* to determine CE variability, the hope is to standardize the error encountered between tests for each specific CE value calculated. The *ε* metric is beneficial to representing the normalized overall error that would typically be encountered for a CE test performed under specific conditions in any other research lab. Also, calculating ε provided a direct means to compare relative errors between cases, while also observing how different test configuration (i.e. fan speed, mounting height, cook-top temperature) influenced the variability of CE.

Summary

In summary, the new ASTM test method is yet to be subjected to long-term repeatability and precision procedures in order to become suitable for standard/certification purposes. Furthermore, there has not been much investigation into the effects of rangehood test configuration on CE performance and CE repeatability. This lack of knowledge is critical to the full understanding of the CE performance metric as well as knowledge gained by rangehood manufacturers and consumers. One of the main contributions of this paper is to investigate how rangehood test configuration and rangehood properties influence CE performance and how to optimize the design criteria of both the rangehood and the test set-up to optimize CE performance and increase accuracy of the CE metric. Another contribution of this dissertation is to develop a consistent means to quantify the repeatability and reproducibility of CE using experimental data and identify/minimize factors of the CE test facility and test procedure that influence CE, as well as CE repeatability and reproducibility. The knowledge gathered from this study will support development of a new Home Ventilating Institute (HVI) certification procedure.

CHAPTER IV

DESIGN AND VERIFICATION OF A TEST FACILITY IN ACCORDANCE WITH ASTM-E3087.18

Overview of Test Facility

In the study reported herein, a CE test chamber was designed and constructed at the RELLIS Energy Efficiency Laboratory (REEL) by following ASTM Standard ASTM-E3087.18, which was developed by LBNL as described by Kim et. al (2018). The standard developed by LBNL utilizes measurements of a tracer gas, namely CO2, at various points in a simulated kitchen to determine capture efficiency (CE).

The following seven subsections, which cover each component and are numbered to be consistent with Figure 3 labels, describe the design and construction of the Capture Efficiency Test Facility in accordance with ASTM-E3087.18. Of specific note, in several instances the component design and capability exceeds the test standard requirements to allow for future research and development, and in each case, these additions were made based on feedback from the Residential Buildings Group at LBNL and the Chief Technology Officer at HVI. It should be noted that a large portion of this chapter was submitted for publication in the Science and Technology of the Built Environment (STBE) academic journal.

Verification of Test Facility Sub-components

Test chamber

The test chamber is a relatively air-tight room that not only simulates a kitchen with a stove and rangehood, but it also contains a majority of the test equipment and instrumentation. The chamber was built to meet the dimensions specified in the ASTM standard, aside from the chamber height that was increased slightly (3.0m vs. 2.5m.) to accommodate future testing of island hoods, with their larger mounting height requirements. Leakage testing was performed on the finished test chamber to ensure the air leakage was no greater than 2.5 air changes per hour (ACH) at 50 Pa gage pressure as specified by the ASTM.

Leakage testing was performed by DPIS Engineering Inc. on January 24, 2018. At a pressure of 50Pa, the leakage was measured to be 57 cfm (27L/s). Given that the volume of the chamber is $56m^3$, the corresponding air changes per hour was 1.73. Given that the maximum leakage of the chamber is 2.5 air changes per hour, the group concluded an acceptably air-tight chamber. A full report provided by DPIS Engineering can be found in Appendix A.

Chamber inlet

According to the ASTM standard, an inlet to the chamber is required that minimizes air drafts and has a maximum average velocity of 0.5m/s. It is important that the inlet be fitted with deflection plates that divert inlet air away from the rangehood unit under test and ensure a chamber depressurization of less than 5Pa as specified by the ASTM.

The air inlet to the chamber was placed 1.8m (6ft.) from the back wall ensuring that the minimum distance of 1m. (3.3ft.) from the unit under test was met, as specified by the ASTM. In order to size the inlet, both a simplified version of Bernoulli’s equation and an air leakage corresponding to two air changes per hour were utilized. Using an inlet velocity of 0.45m/s, the required inlet diameter was determined to be 0.27m. (10.5in.).

To ensure that inlet air does not disturb the flow pattern of the unit under test as specified by the ASTM standard, a diffuser plate similar to that used by LBNL (Kim, 2017) was built and installed as shown in Figure 6. The diffuser plate delivers inlet air in all directions except towards the rangehood and emitter assemblies. It is important to note that the ASTM standard does not specify size requirements for the inlet, only the maximum velocity.

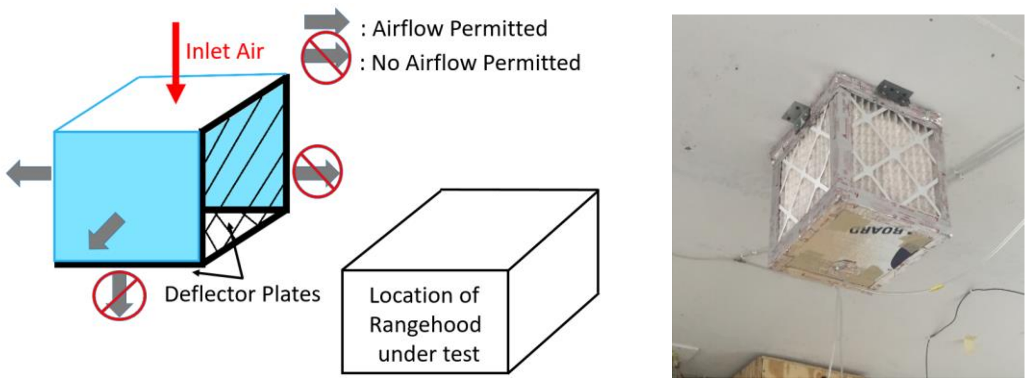


Figure 6: Schematic showing inlet air being directed away from unit under test (left) and custom diffuser plate placed on inside of chamber (right)

Chamber exhaust

The chamber exhaust system has two functions. First, it connects the outlet of the rangehood to the outdoors where the air is exhausted. Second, as specified by the ASTM, the exhaust system must be capable of measuring air flow with an accuracy of ±2.5 L/s (5.3 cfm) or 5% of measured flow, whichever is greater.

The exhaust diameter is dictated by the geometry of the flow measurement apparatus used in the exhaust duct (venturi tube). A venturi tube with an 8” diameter and a 4” throat, which is shown in Figure 10, was selected for several reasons, including low uncertainty, short entry length and ease of fabrication. The venturi tube utilized was fabricated in accordance with ISO 5167-4, a standard for measurement of fluid flow by means of a pressure differential device (ISO, 2003).

Figure 7: Venturi tube used for flow measurement

The venturi tube was fabricated by Brazos Industries in Bryan, TX in accordance with ISO 5167-4 for measurement of fluid flow by means of a pressure differential device. The venturi tube was inspected by Brazos Custom Fabrication and lab personnel to ensure conformance to the standard. A detailed drawing used for inspection can be found in Appendix A.

In order to maintain less than 5% uncertainty in the flow measurement as specified by ASTM-E3087.18, certain geometries within the venturi tube had to be adhered to. These geometric requirements are presented below:

- Diameter ratio (β) between 0.4 and 0.7 *(no additional uncertainty)*
- Diameters between 200mm and 1200mm *(no additional uncertainty)*
- Fabricated using welded sheet iron *(1.5% baseline uncertainty)*
- 3 duct diameter entry length *(additional 0.5% uncertainty)*

- Diameter deviation (circularity) of no more than 10% from mean diameter *(additional 0.5% uncertainty)*
- Uncertainty in discharge coefficient *(additional 1% uncertainty)*

Following the above geometric requirements, the venturi tube as fabricated has an uncertainty of 3.5%, which is less than the maximum allowable 5% uncertainty specified by the ASTM standard.

As specified by ASTM-E3087.18, an auxiliary-fan and damper were installed in the exhaust system to allow the rangehood flowrate, Q_{hood}, to be adjusted to specific operating points (i.e. flowrates/static pressures). The end of the exhaust system was fitted with a duct termination (vent-cap), to allow air from the rangehood to be exhausted outdoors, without allowing air/contaminants/water to enter the chamber from the outside.

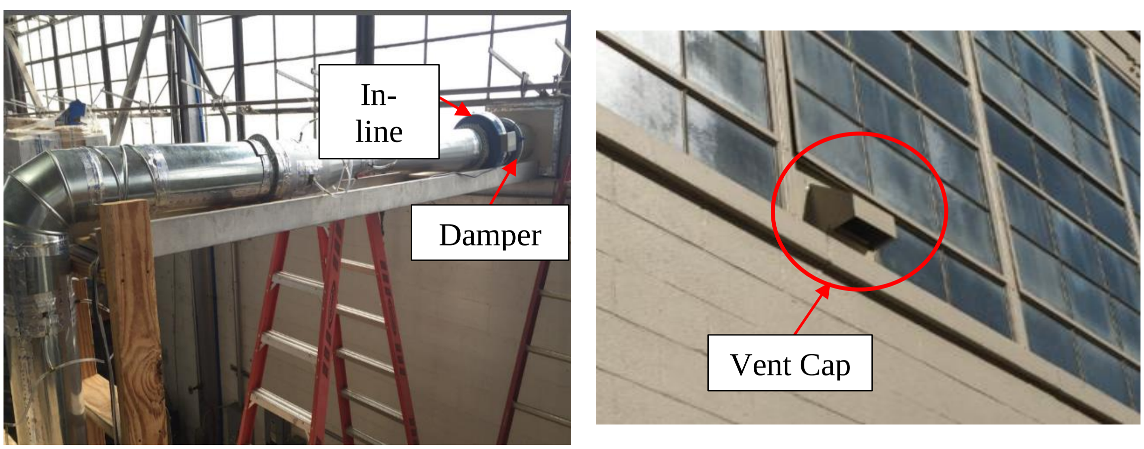


Figure 8: In-line fan and damper used in exhaust system

With the exhaust components in place, an additional leakage test was performed on the exhaust system. The leakage test yielded a result of 2.7 cfm (1.3 L/s) leakage at 25 Pa, which is less than the ASTM specified value of 2.5 L/s at 25 Pa.

Rangehood unit under test

The ASTM-E3807.18 test standard is currently written for residential rangehoods up to 0.9 m (35.4 in) wide with volumetric air flows up to 200 L/s (423.8 cfm). Furthermore, for all testing, ASTM-E3087.18 specifies using the manufacturer suggested mounting height, with a minimum mounting height of 0.5 m (19.7 in) being required. Therefore, proper measures were taken during facility construction to ensure that rangehoods could be mounted at various heights and sit flush with the back wall/adjacent cabinets while under test. Specifically, two separate track systems were designed to accommodate a range of widths and mounting heights that one might encounter in rangehood testing. The first track system (rangehood track) was designed to accommodate different mounting heights. The second track system (cabinet rails) was designed to accommodate different rangehood widths by allowing the cabinets specified by the ASTM standard to slide laterally and to be placed flat against a test unit. Also, a custom wooden frame for mounting different size rangehoods was built. Both track systems along with a custom wooden mounting frame are shown in Figure 9.

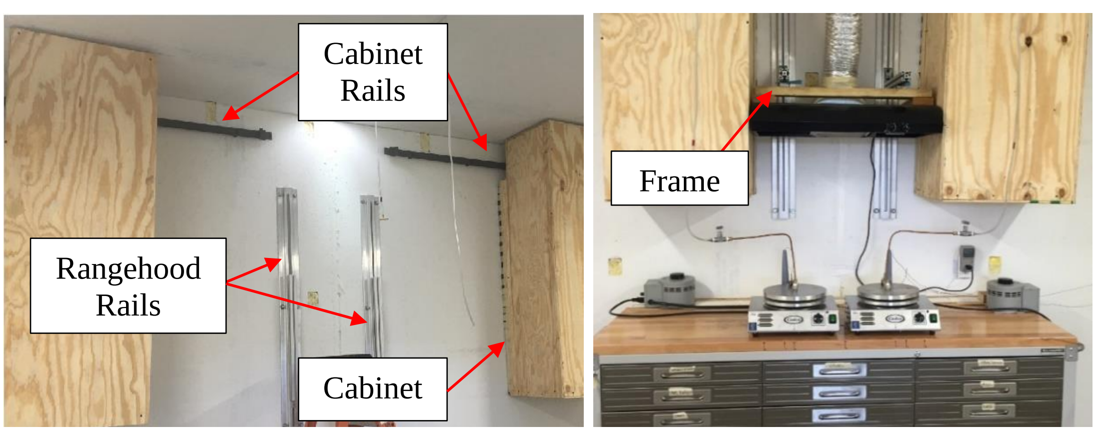


Figure 9: Interior of chamber with adjustable cabinet/rangehood rail system (left) and range hood mounted to custom mounting frame (right)

Cook-top

ASTM-E3087.18 requires varying locations of the heating elements depending on rangehood size. In order to accommodate variability in burner placement, the cook-top was comprised of a workbench and three portable electric burners. The workbench, which is shown in Figure 10, was sized to be 76 in. (1.9 m) in width so that the counter top could be extended the minimum 20 in. (0.6 m) on each side of a 36 in. (0.9 m) (max) wide rangehood as specified by the ASTM. The workbench chosen was also able to meet the ASTM depth criteria with a slight modification consisting of installing a custom spacer that brought the workbench forward 6 in. (0.2 m) as shown in Figure 10.

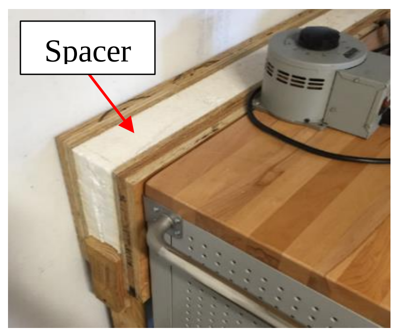


Figure 10: Workbench used to simulate counter-top (left) and frame used to bring workbench forward (right)

The ASTM specifies that cabinetry be installed on both sides of the cook-top so that the cabinetry extends laterally at least 0.50 m (20 in.) and has a depth of 0.30 – 0.40 m (12 – 16 in.). Furthermore, the ASTM specifies that the cabinetry must touch the ceiling and extend down vertically 1.0 – 1.1 m (39 – 43 in.). Cabinetry was installed on both sides of the cook-top, extending laterally 0.56 m (22 in.) with a depth of 0.36 m (14 in.). In order to accommodate the higher ceiling, cabinetry was mounted to touch the ceiling and extend down 1.60 m (63 in.) rather than the recommended 1.1 m (43 in.). The cabinet deviation was necessary in order to maintain a fixed distance of 0.50 m (20 in). between the countertop and cabinetry, as shown in Figure 11. Since the distance between the counter-top and cabinets was consistent, it was assumed that this deviation would have no effect on CE measurement. Additionally, this deviation was made with input from the Residential Buildings Group at LBNL.

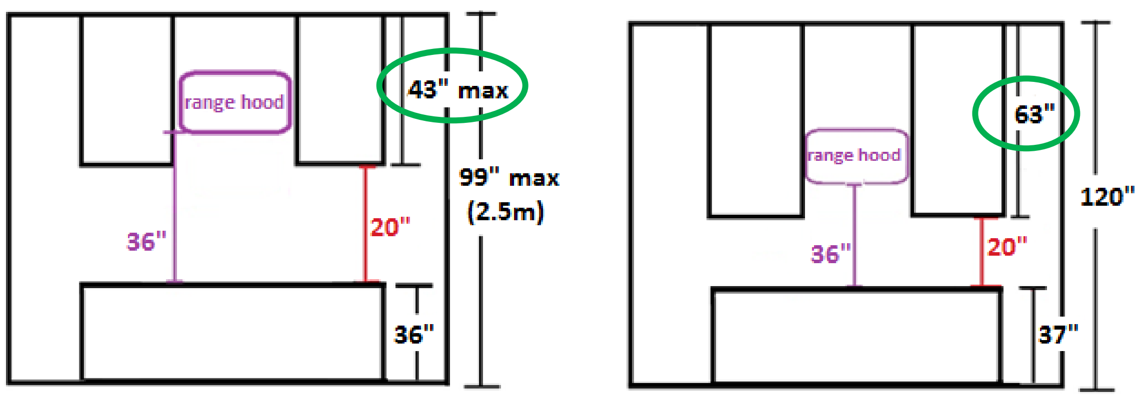


Figure 11: Cabinet dimensions specified by ASTM (left) and cabinet dimensions utilized at REEL (right) - deviation necessary to maintain distance between countertop and bottom of cabinetry circled in green

Three portable electric burners were selected to simulate the heating elements on a kitchen stove, with each burner having a diameter of 7.5 in. (191 mm), which is within the acceptable range of 200 ± 10 mm specified in ASTM-E3087.18. The electric burners were fitted with magnetic thermocouples (not pictured) in order to withstand high temperatures without melting the thermocouple wiring.

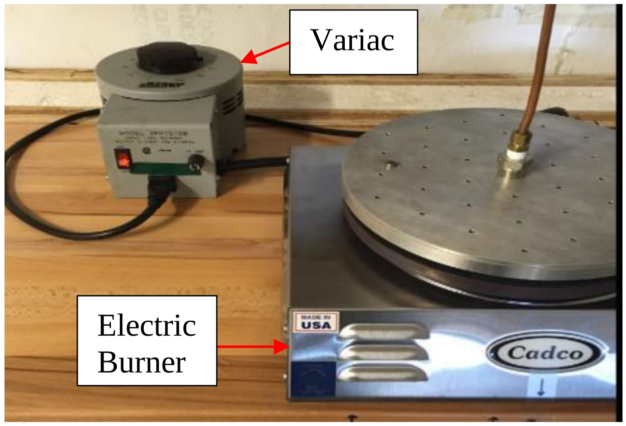


Figure 12: Electric burner and variac used to simulate cook-top

ASTME-E3087.18 does not specify that the power supplied to each burner be regulated; however, the previous 2017 standard specified regulating power to 1 kW ± 0.1kW. Using variable power transformers (i.e. variacs) connected in-line with the burners to regulate the power, it was determined that the electric burners used 1.4 kW of power during operation. Even though it was not required by the 2018 standard, the variacs were set to 71% capacity (i.e. 1/1.4 kW) of full power during the verification phase, to matched the 1 kW specified in the 2017 standard and the burners were set to various temperature settings to accommodate different rangehood airflow/CO_2 injection rates.

CO_2 emitter system

Each CO_2 emitter assembly shown in Figure 12 consists of two main pieces: a 'Lower Plate' and an 'Upper Plate'. The 'Lower Plate' consists of a solid circular disk that the 'Upper Plate' is mounted to, while the 'Upper Plate' consists of two surfaces fastened together. The two parts of the 'Upper Plate' are the 'Top Surface' and 'Bottom Surface', which are shown in Figure 13 and were custom-fabricated to meet the ASTM-E3087.18 specified dimensions. A full detailed drawing of the CO_2 emitter assembly components is shown in Appendix B for reference.

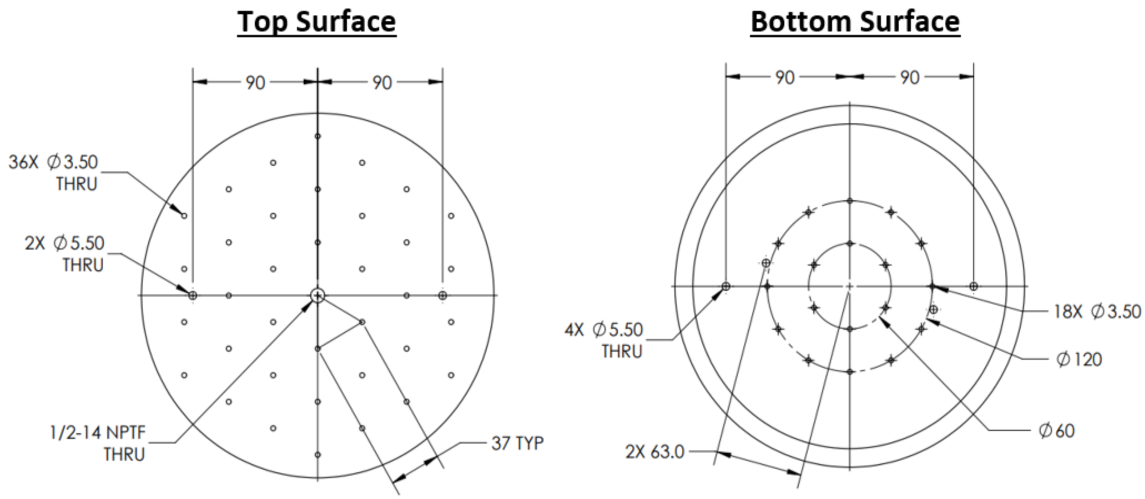


Figure 13: ASTM specified dimensions for the Top Surface (left) and Bottom Surface (right) of the CO_2 emitter Upper Plate (dimensions shown in millimeters as specified by the ASTM)

The 'Upper Plate' serves as the CO_2 emitter as it has two surfaces assembled together with holes for CO_2 to flow in and out of. There is an additional gap between the 'Upper Plate' and the 'Lower Plate' to ensure uniform CO_2 emission in the upward/downward direction without influencing CO_2 emission from nearby plates or the electric burner. In order to manage the CO_2 volumetric flow to the emitter plates, a digital mass flow controller was used.

ASTM-E3087.18 is currently written for rangehoods with a maximum flowrate of 200L/s (423cfm) and specifies a CO_2 injection rate less than 0.5% of this airflow. Therefore, the maximum CO_2 injection rate was calculated to be 1L/s (60lpm). Additionally, ASTM-E3087.18 specifies an accuracy of ±1% of CO_2 mass flow. In order to manage the combined volumetric flow to the emitter plates a Cole-Palmer mass flow controller was purchased (Part No. 32907-75). The mass flow controller used is shown in Figure 14.

Figure 14: Mass flow meter used in test facility

The instrument in Figure 14 is capable of measuring CO_2 mass/volume flowrate in the range between 0-100 lpm with +/- 0.8% accuracy, thus satisfying the ASTM standard. The mass flowmeter selected is capable of measuring mass/volume flowrate in the range between 0–100lpm with ±0.8% accuracy, thus satisfying the ASTM standard.

CO_2 detection system

The CO_2 detecting system consists of a CO_2 sensor manufactured by PP Systems (Part No. SBA-5). The gas-analyzer grade sensor has a 0-5000ppm range of with 0.3% accuracy. In order to maintain accuracy, the sensor performs auto calibration using an 'auto-zero' feature.

The 'auto-zero' column brings air into the unit that is scrubbed free of CO_2 in order to set a reference point for the infrared technology utilized by the sensor to determine CO_2 concentration. Ambient air is drawn into the column and passed over Sofnolime beads, which remove CO_2 from the air before passing into the SBA-5 sensor. Given that the maximum CO_2 concentration in the exhaust is not expected to exceed 3000ppm, and 0.3% of 5000ppm is 15ppm, the group felt this was sufficient to meet the ASTM standards.

In addition, since ASTM-E3087.17 specifies that all tracer gas concentrations shall be measured by using the same instrument, the group decided to procure a directional control (solenoid) valve that feeds into the SBA-5 sensor. The solenoid valve is provided by Valco Industries (Part No. C45R-8148EMT).

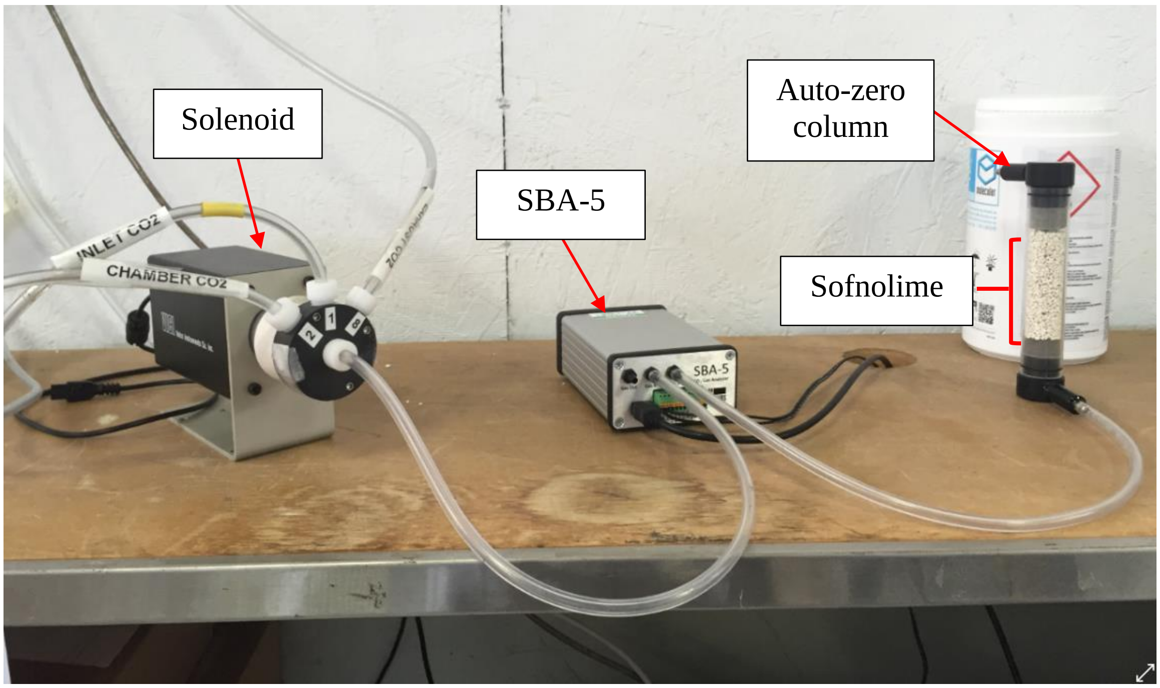


Figure 15: Solenoid valve and SBA-5 sensor used in test facility

The directional control valve has the capability for cycling between eight different sampling points. However only three sampling points are occupied on the solenoid valve, with those sampling points being inlet, chamber and exhaust.

In order to conform to the ASTM standard, certain measures were taken to ensure proper placement of the sampling tubes. The chamber sampling tube was fixed to an adjustable frame and adjusted to one-half the mounting height of the range hood.

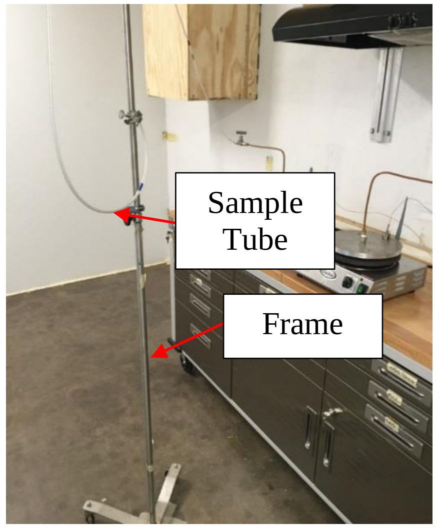


Figure 16: Adjustable frame for measuring chamber CO_2 concentration

Similarly, the exhaust sampling tube was positioned 10 duct diameters downstream from the range hood. The exhaust sampling position had five sampling points across the duct cross-section as shown in Figure 17.


Figure 17: Five sampling points across exhaust duct

Test procedure

In conjunction with designing/building a CE Test Facility, test procedures were also developed in this study to ensure that the experimental testing would be performed in a proper and uniform manner independent of the operator. Specifically, requiring that these procedures be followed by all operators will ensure that the reliability and accuracy of the data taken is maximized.

The following is an overview of the test procedure that was adopted and used in this study for testing:

1. Check/record chamber air temperature.
2. Install rangehood.
3. Turn on rangehood and hot plates, then wait for hot plates to reach 160 ± 10°C.
4. Turn on 'Instrumentation Power Strip' and plug in CO_2 heater.
5. Open 'Master LabVIEW VI.vi' and reference 'Software Operating Instructions' to navigate user interface.
6. Introduce CO_2 tracer gas by opening the regulator valve on the CO_2 tank.
7. Wait until the time shown in the 'Steady-state time (Tss)' window of VI has passed. The steady-state time is defined as the time required for the chamber to complete four air changes as defined below:

$$T_{SS} = 4\frac{Q_{hood}}{V_{chamber}}$$

- T_{SS}: steady-state time (min.)
- Q_{hood}: Air flow rate through the rangehood (cfm)
- $V_{chamber}$: Volume of chamber (ft^3)
- *4*: Factor considering four air changes

8. Click ‘Record’ in LabVIEW vi and record 10 measurements of the following values over a ten-minute period: ‘C_exhaust’, ‘C_chamber’, ‘C_inlet’, ‘Q_hood’, Power to heating elements, cook-top temperature, chamber temperature.

- Note: 10 sets of measurements means that for each of the parameter values (i.e. C_exhaust, C_chamber, etc.) all values shall be measured before taking the second measurement of any one value and so forth, up to 10 sets.

9. Calculate the average of each parameter value using the 10 sets of measurements recorded in the previous step.
10. Calculate one Capture Efficiency (CE) using the average values as follows:

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

11. Take photographs of test set-up for documentation.

Preliminary Results

In support of a preliminary study using this newly constructed test-facility, 81 capture efficiency (CE) tests were performed, with data being gathered from seven different rangehood units operating under 22 unique test configurations (i.e. speed setting, mounting height and assist fan usage). In addition to determining CE, the uncertainty in CE was also calculated using a preliminary precision and bias procedure outlined in ASTM-E3087.18.

Variability was investigated by using the coefficient of variation (ε) for repeated tests to provide insight on the magnitude of the CE discrepancy relative to the average CE of these repeated tests. Additionally, the standard deviation between consecutive CE measurements during a specific CE-test was analyzed to compare with previous LBNL data. Given that all past LBNL studies show a positive correlation between CE and rangehood flowrate, a focus of this preliminary analysis was given to understanding the effects that rangehood flowrate has on CE, along with CE-uncertainty and variability of CE.

Preliminary Capture Efficiency Results

It can be seen in Figure 18, which is a plot of CE versus rangehood flowrate, that capture efficiency (CE) ranged between 50% to 92% over a flowrate range of 82 cfm to 234 cfm.

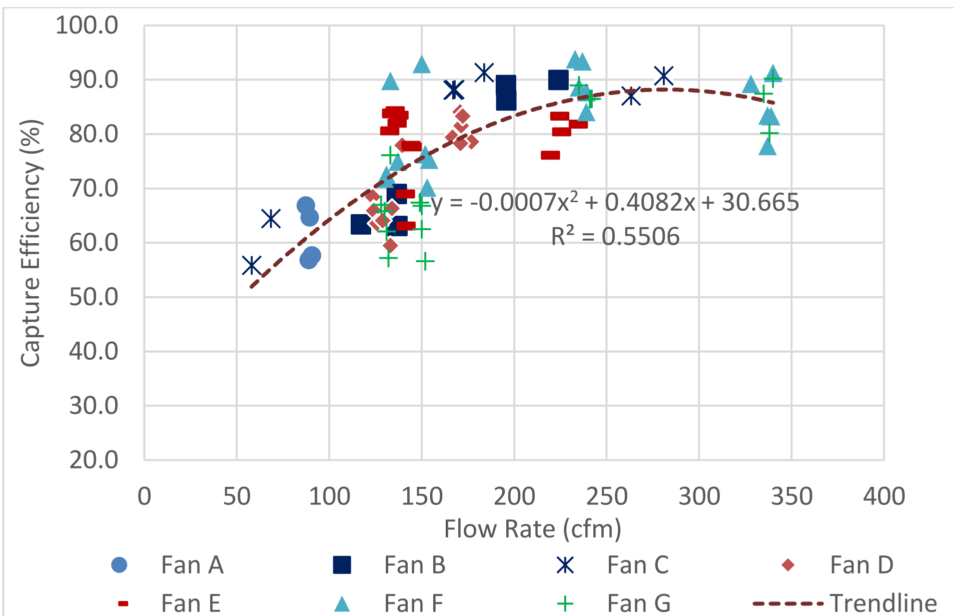


Figure 18: Preliminary Capture Efficiency vs. Flowrate for all fans

As expected, the results in this analysis show CE increasing as flow through the rangehood increases; however, beyond a certain point a leveling off occurs and then with further increases in flowrate, one can observe a slight negative impact on CE. The data in Figure 12 shows similar trends to previous LBNL studies (Walker,2016 and

Kim,2017), other than the fact that there are not observable decreases in CE at high flowrates.

Table 1 shows test results for one rangehood unit, which includes standard deviation between consecutive CE measurements during one test, uncertainties and ε values. Test data for the other five rangehoods are presented in Appendix C. It should be noted that the data presented in Table 1 and Appendix C is considered preliminary and was mostly taken immediately after the test-facility was fully constructed to understand its operations and full testing capabilities. These results are considered initial and may change as the body of CE data increases with additional studies.

Table 1: CE test results for one rangehood test unit (Fan D)

Test Fan	Test No.	Speed	Q_ avg. (cfm)	Mt. Ht. (in.)	CO_2 (L/ min)	Rt. Avg. Temp (°C)	Lt. Avg. Temp (°C)	CE (%)	St. Dev (%)	δ (%)	COV (ε) (%)
Fan D	#1	Low	127	16	15	156	162	65.8	1.82	2.13	1.7%
Fan D	#2	Low	124	16	15	155	150	68.5	5.18	2.14	
Fan D	#3	Low	124	16	15	150	155	66.1	1.21	1.24	
Fan D	#4	Low	124	16	15	151	152	65.9	1.45	1.80	
Fan D	#5	Low	134	16	15	154	167	66.3	1.13	1.18	
Fan D	#6	Low	127	13.5	15	148	163	63.3	1.56	1.74	3.3%
Fan D	#7	Low	126	13.5	15	156	163	63.5	1.44	1.24	
Fan D	#8	Low	129	13.5	15	147	170	64.1	1.37	1.26	
Fan D	#9	Low	133	13.5	15	153	159	59.5	1.38	1.42	
Fan D	#10	High	169	16	20	155	160	80.4	0.93	1.12	1.0%
Fan D	#11	High	177	16	20	150	164	78.6	1.19	1.44	
Fan D	#12	High	168	16	20	151	157	80.2	1.22	1.81	
Fan D	#13	High	167	16	20	157	174	79.4	0.63	0.85	
Fan D	#14	High	171	13.5	20	147	159	81.5	0.81	1.46	3.1%
Fan D	#15	High	171	13.5	20	153	161	84.1	0.64	1.06	
Fan D	#16	High	172	13.5	20	154	167	83.3	0.99	1.58	
Fan D	#17	High	171	13.5	20	163	170	78.3	1.14	1.45	

From these results, and all others in Appendix C, it was observed that 83% of cases had standard deviations less than 1.5%, while 93% had standard deviations less than 2.0%. Even though this preliminary data in its entirety provides insight into the operations of this new facility and general relationships between flowrate and CE, it is not recommended that the data be used for any additional analyses, such as the effects of mounting height, CO2 injection rates or burner temperatures on CE. In fact, the burner temperatures for some of this preliminary data do not satisfy the ASTM requirement of 160±10°C. Rather, the data reported herein was important for evaluating system control, data acquisition and methodologies for determining variability.

Preliminary Uncertainty Results

Uncertainties were calculated in accordance with a preliminary procedure described in Section 11 of ASTM-E3087.18 and outlined in Appendix D. The resulting uncertainties in CE ranged from 0.7–3.3%, with uncertainties appearing to be independent of flowrate as shown in Figure 19.

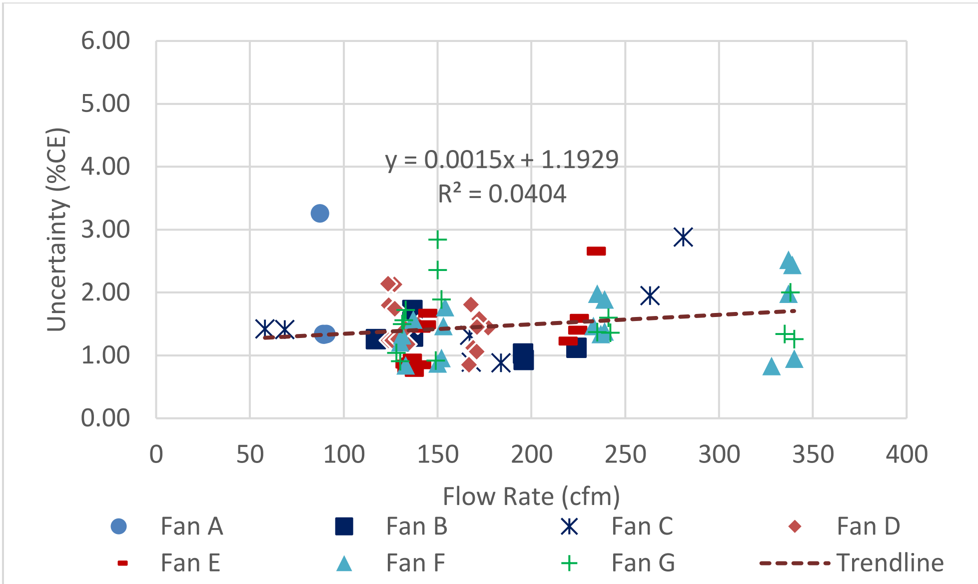


Figure 19: Capture Efficiency vs. Uncertainty for all fans

Out of 81 tests performed, 72 cases (89%) had uncertainties in CE less than or equal to 2.0%, and only 5 cases (6%) had uncertainties greater than 2.5%.

Figure 20 is a box-and-whisker plot that groups the values for uncertainty by flowrate to better understand how flowrate influences CE-uncertainty. It should be noted that the sample size shown in parentheses represents the number of values in each group (i.e. number cases with-in airflow range).

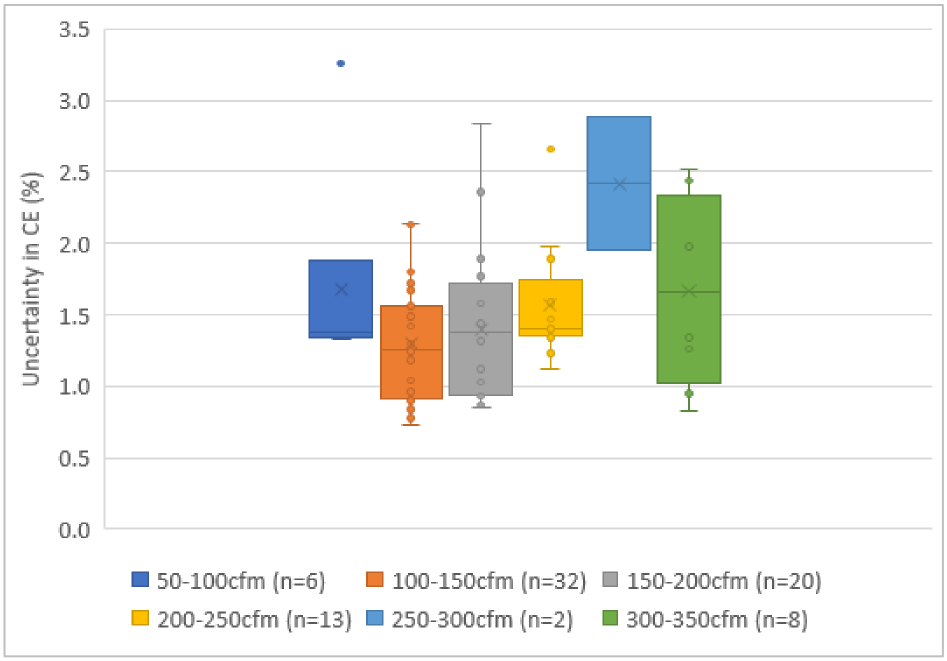


Figure 20: Uncertainty for all fans grouped by flowrate

From this graph, it can be seen that uncertainty in CE is independent of flowrate. Again, because of the use of preliminary data, the above is presented here exclusively as an example of how tools can be applied to future analyses.

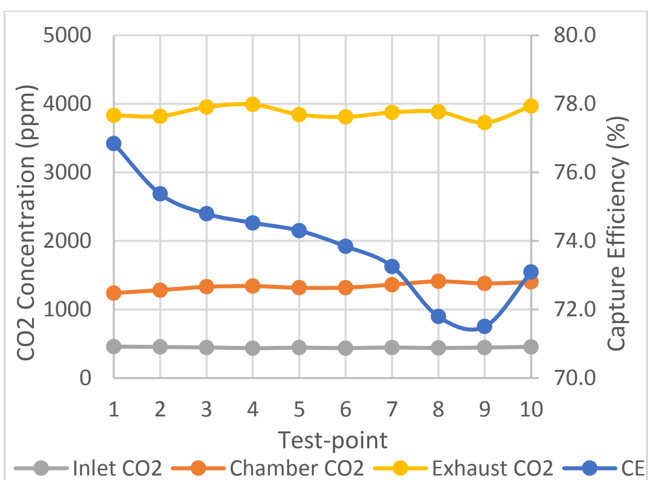
Preliminary Variability Results

For those unique tests (i.e. fan, speed, mounting height) that were performed more than once, variability was determined based on calculation of the coefficient of variation (ε). To reiterate, ε represents the percentage in which the calculated CE varies from the average CE. For 22 scenarios performed more than once, ε was greater than 10% for only 2 of the scenarios, indicating that CE is expected to deviate less than 10% (i.e. +/-5%) by using the current test-facility/procedure. Additionally, 17 out of 22 cases had ε values less than 6%, with those tests with higher CE-values typically having lower values for ε.

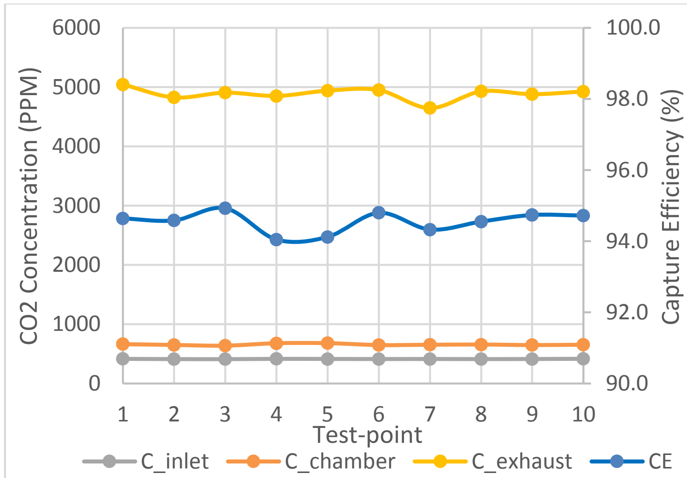
During preliminary testing and analysis of the results, it was observed that some tests showed discrepancy in the standard deviation between consecutive CE measurements during a specific test that were greater than those reported by Walker et. al. (Walker, 2016) and Kim et. al. (Kim, 2017). After closer inspection of the test results, two key observations were made, and are discussed below, that could affect the application and promulgation of ASTM-E3087.18.

ASTM Prescribed Steady-state Time

First, as observed by Walker et. al. (Walker, 2016) some rangehood fans and flowrates require more than four air-changes to reach steady-state (i.e. less than ±1.5% variation in CE), and in some cases as many as eight air-changes are needed for steady-state. Figure 21 shows the progression of CE, and the three concentrations of CO_2 used in its calculation, over time for two cases analyzed in this study. As indicated in Figure 21, one fan did not reach steady-state after completion of four air-changes, whereas the other one did.



(A)



(B)

Figure 21: Variations in CE and CO_2 concentration after four air changes for test that did not reach steady-state (A) and test that did reach steady state (B)

Figure 21 shows the 10 test-points taken during the minimum 10-minute period prescribed by the ASTM, with each point taking about one minute and test-point 1 starting after four air-changes. As can be seen in Figure 21a, the inlet CO2 and exhaust CO2 remain relatively constant, compared to the chamber CO2, which shows a gradual increase over time. The increase in chamber CO2 directly correlates with a decrease in CE, which can also be seen in Figure 21a. It is important to note that CE was initially 77% before dropping to about 75% and appearing to level off around 73%.

In order to account for this inconsistency in CE-values after the four air-changes prescribed by ASTM-E3087.18, it is recommended that future standards be written to impose restrictions on the allowable difference between consecutive CE-values before proceeding with the 10 test-points. It is also important that CE be continuously monitored to ensure no increasing/decreasing trends occur, as shown in Figure 21a, indicating that steady state has not been reached. Rather, as an indication of steady-state, one would expect to see slight fluctuations around an average value, as shown in Figure 21b

<u>Inlet Filter Selection</u>

Additionally, it was observed that although the analysis used in the present study was able to yield a reasonable approximation for the inlet size based on average inlet velocity, the filters chosen can have significant effects on localized velocities. Localized velocities as high as 1.1m/s were observed on some faces, although other regions on the same face showed less than 0.5m/s velocity. Upon making this observation, the diffuser plate was remodeled to incorporate more porous filters (i.e. a fiberglass vs. pleated filter) and a larger area, as shown in Figure 22, which reduced all local velocities below ASTM specifications

Figure 22: Old Pleated Filter (Left) and new fiberglass filter (Right)

Summary

Capture efficiency (CE) is defined as the fraction of cooking contaminants captured by a rangehood and exhausted to the outdoors, as opposed to those contaminants that enter the residence. Understanding of CE is crucial to the efficient design of rangehoods as well as human health and safety; however, there is a lack of experimental studies in measuring CE and the factors influencing CE, mainly because test facilities/procedures have not been readily available for performing these tests or investigations for CE. Even though an ASTM testing methodology was recently developed, there are currently no HVI requirements or ASHRAE standards specifying acceptable values of rangehood CE performance. However, the results of this study that focused on design and construction of a CE test-facility, along with taking and evaluating preliminary CE test-data, will facilitate the understanding of CE while promoting development of CE requirements/standards.

In this Chapter, the steps taken to design, build and operate a fully operational capture efficiency (CE) test facility for the purpose of measuring the CE performances of wall-mounted rangehoods is presented. In fact, the facility described herein is the first test facility built from the ground up following guidelines promulgated by a standard recently implemented, namely ASTM-E3087.18: Standard Test Method for Measuring Capture Efficiency of Domestic Range hoods. However, a non-proprietary operating facility with similar characteristics was developed earlier at Lawrence Berkeley National Laboratory (LBNL), and it was used to perform testing in support of developing ASTM-E3087.18, which quantifies rangehood CE by using a tracer gas to simulate cooking contaminants. With the existence of these two facilities, it becomes possible for the first time to investigate how different test facilities and range hood configurations influence CE measurements, as well as the variability of CE (ε).

The new CE test-facility described herein consists of seven key components: the test chamber, rangehood (unit under test), cook-top, CO_2 emitter system, chamber inlet, chamber exhaust and CO_2 detection system. After completing the test-facility, 81 tests were performed on seven different rangehoods in order to provide an initial understanding of CE and its uncertainty/variability. Results showed that CE ranged from 55.8–93.8% for flowrates of 58–340cfm, with CE increasing as airflow through the rangehood increases.

Based on preliminary test-data, CE uncertainty/variability were also studied, but by using only a limited amount of preliminary test-data these results are considered initial and may change as the body of CE-data is increased with additional studies. It was found that CE always had an uncertainty less than 3.3%. Additionally, for all test set-ups (i.e. mounting heights and operating speeds) performed more than once, the capture efficiency was repeatable to within 10% of the average CE for 91% of cases and within 6% for 77% of cases. A general trend from the preliminary data is that increasing the flowrate improves CE, while having minimal effect on variability/uncertainty. Additionally, increasing flowrate beyond a certain point appears to have a negative impact on CE for some fans, meaning that there is a 'maximum' flowrate, beyond which the CE may begin to decrease, for any number of reasons that still needed to be investigated.

CHAPTER V

THE EFFECTS OF COOK-TOP TEMPERATURE ON CAPTURE EFFICIENCY USING ASTM-E3087.18

Overview

Currently there are no HVI or ASHRAE standards for characterizing the capture efficiency (CE) performance of a range hood, with CE being defined as the percent of total cooking contaminants released that are captured or exhausted out of a range hood. Recently, the American Society of Testing and Materials (ASTM) developed ASTM-E3087.18, which is a methodology and testing procedure for measuring the CE of residential, wall-mounted range hoods. However, this standard is based primarily on research data from one test facility located at Lawrence Berkeley National Laboratory (LBNL). Thus, it is possible that the methodologies and procedures in the standard, along with hardware setups, will undergo modifications and revisions as usage of the standard expands beyond the LBNL original test facility that the standard is based on. As an example of a change in the standard, ASTM-E3087.18 recently underwent a revision changing the surface temperature of the simulated cook-top from 200°C to 160°C. This decision was reported to be based on 200°C presenting problems for laboratory safety and high levels of radiation heat transfer potentially leading to inconsistencies in test results. Concerns were also raised as to 200°C not being representative of cooking events encountered in a typical residence. Even though the ASTM standard has settled on a 160°C temperature, there is no evidence in the open literature of research having been done to investigate the viability, including the repeatability of the new test procedure with its reduced temperature. Also, of special importance and concern, there are no studies of whether or not the cook-top surface temperature can influence CE measurements and if so then in what manner.

Since questions regarding cook-top temperatures for CE testing still exist, there is a need for a thorough investigation of the effects of cook top temperature on CE. In the study reported herein, five range hoods were CE tested at both a high flowrate and a low flowrate by using one fixed mounting height and a cook-top temperature of 160°C, and then repeated by using a cook-top temperature of 200°C, for the purpose of observing the effects of cook-top temperature on CE. The influence of cook-top temperature on CE was investigated further by performing limited testing on two out of the five range hoods at a third temperature of 130°C.

As a final step, a thorough analysis was performed on the data file that was created from CE testing the five different range hoods, operating at two different speeds and for variable surface temperatures and/or mounting heights, to achieve a full understanding of cook-top temperature effects, along with making ASTM standard recommendations when appropriate. It is important to note that a baseline mounting height of 27in. was used for traditional range hoods and 16in. for over the range (OTR) microwaves in order to minimize observed changes in CE caused by parameters other than cook-top temperature. In addition, each unique case was tested three times with one mandatory dismount/re-mount during the test cycle to observe how cook-top surface temperature influences not only CE, but also its repeatability and reproducibility. It should be noted that a large portion of this chapter was submitted for publication in the Science and Technology of the Built Environment (STBE) academic journal.

Problem Statement

The focus of this chapter is to investigate how the temperature of the cook-top beneath the range hood influences the capture efficiency (CE) of a residential, wall-mounted range hood. Past case studies have shown that the orientation of the burners on the cook-top can affect the perceived CE performance of a range hood (Singer, 2011 and Delp, 2012); however, neither of these studies emphasize the influence of cook-top temperature. It should be noted, that both of these experiments used a natural gas stove and pots of water that did not necessarily come to a boil. Furthermore, another study done by Kim et. al. showed that the type and place of a tracer gas emitter can influence CE by as much as 10% (Kim, 2017). In line with the above studies of the other effects on CE, it is also important to understand the effects of cook-top temperature on CE in order to ensure an accurate, repeatable and reliable method for quantifying range hood CE.

Experimental Methods

Test Facility

Testing of all range hoods reported herein was performed by using the aforementioned test chamber that was designed and built at the RELLIS Energy Efficiency Laboratory (REEL) at Texas A&M University. Of special note, this facility is the first built from the ground up at a public institution by following the guidelines of the recently published ASTM-E3087.18 Standard. A second facility at LBNL that meets ASTM standard guidelines was built even earlier, but it was built prior to the release of the standard, and in fact it was used to develop the original standard (Kim, 2018).

The test chamber used herein has dimensions of 4m x 5m (13.1ft x 16.5ft) with a ceiling height of 3m (10ft). To reiterate, the ceiling was built slightly higher than the 2.5m specified by the ASTM in order to allow for future testing of island range hoods that require higher mounting heights. Of special importance, the higher ceiling was supported by a number of organizations that participated in development of the original standard with the idea that the higher ceiling is not expected to affect the CE measurement. The chamber has a leakage rate of 1.7ACH corresponding to 50Pa, which is less than the 2.5ACH specified by ASTM. The exhaust duct was built in accordance with ASTM-E3087.18 and has a leakage rate of 1.3L/s (2.7cfm) at 25Pa, which is less than the ASTM specified value of 2.5L/s at 25Pa.

Airflow through the exhaust duct is measured by using a venturi tube built in accordance with the International Standard Organization (ISO) Standard ISO5167-4 for measurement of fluid flow by means of a pressure differential device. As detailed in Appendix E, the venturi tube has an uncertainty of 3.5% of the measured airflow, which is less than the ASTM-E3087.18 required value of 5% or 2.5L/s (whichever is greater).

Test Procedure

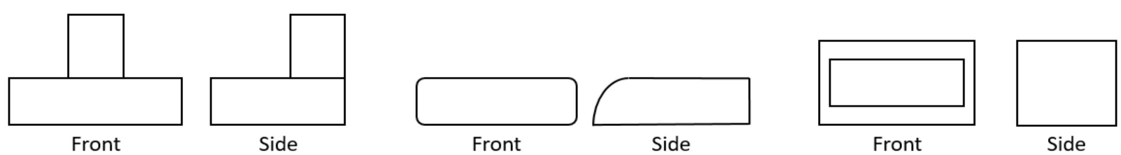
A uniform test procedure that is slightly different from that used during the preliminary verification of the test facility was applied to all range hood tests performed in support of this study of surface temperature effects on CE. The test procedure followed involved testing each range hood three times, at their respective high/low speeds and primarily at one fixed mounting height (27in.). Two of the three tests were performed consecutively (CE 1 and CE 2) in accordance with ASTM-E3087.18 to observe the effects of surface temperature on CE repeatability (i.e. difference between tests run consecutively). Next, the range hood was dismounted/re-mounted and tested again (CE 3) to observe the effects of surface temperature on CE reproducibility. In all tests performed, specific attention was given to the trend of CE with time to ensure a steady-state CE was achieved. The test procedure for one of the five range hoods tested is broken down for clarity below:

1. Install range hood and set to desired speed (lowest or highest setting on range hood)
2. Heat 'Top Surface' to desired surface temperature (130°C, 160°C or 200°C ± 10°C)
3. Introduce CO2 tracer gas at 0.5% of range hood airflow rate
4. Wait until chamber undergoes 4 air changes
5. Take a minimum of 10 sets of measurements of three concentrations (C_exhaust, C_chamber, C_inlet), meaning that a set is made up of three measured values of the three different concentration values.
6. Plot the CE for each set of measurements and continue taking sets of measurements until the slope across the most recent 10 CE values has a magnitude less than 0.15 (i.e. less than 1.5% change in CE across all 10 measurements). See Appendix F for reference plot.

7. Take the last 10 of measurements and calculate an average value for each of the three concentrations, then use Equation 1 to calculate one final CE value, indicating that the CE test is complete.
8. Open door after the test is complete and clear out the test chamber until the difference between C_chamber and C_inlet is less than 50 ppm.
9. Keep range hood running at set speed and repeat steps 3 – 7 to calculate CE for *Test 2* while making sure that the surface is at the test temperature.
10. Dismount range hood
11. Re-install range hood and repeat steps 2 – 7 to calculate CE for *Test 3*.
12. Repeat steps 1 – 11 for all 5 range hoods analyzed in this study.

Test Scenarios

As noted previously, the five range hoods tested were of three different designs typical of residential wall-mounted range hoods, namely: two wall-chimney, two under cabinet and one over-the range (OTR) microwave, with representations of the three different profiles being shown in Figure 23.



(A) Wall-chimney | (B) Under cabinet | (C) OTR-Microwave

Figure 23: Three range hood design types analyzed in this study: (A) Flat-bottom, (B) Traditional Sump and (C) OTR-Microwave

The following distinctive features should be noted for each style of range hood: wall-chimney has a square body, under cabinet is more rounded and the OTR is identical to a standard microwave.

Three range hoods, specifically one of each design type, were chosen to perform testing using an additional 'Top Surface' temperature of 130°C ± 10°C in order to investigate how testing outside of the previously specified ASTM temperature ranges influences CE as well as CE repeatability/reproducibility. Table 1 shows a breakdown of all the tests performed in this study.

Table 2: Breakdown of various test scenarios analyzed in cook-top temperature study

Fan ID	Low Speed (cfm)	High Speed (cfm)	Range hood Design	Temperatures (°C)
Fan A	160	340	Wall-chimney	160, 200
Fan B	140	250	Under cabinet	160, 200
Fan C	160	340	Wall-chimney	130, 160, 200
Fan D	160	300	Under cabinet	130, 160, 200
Fan E	160	270	OTR Microwave	130, 160, 200

Results

As previously mentioned, there are multiple factors that can influence the capture efficiency (CE) and CE repeatability/reproducibility. Factors that can influence CE include, but are not limited to, the range hood type, airflow rate, mounting height and even test facility characteristics (e.g. inlet, tracer gas emitters, burner placement, etc.). The following section presents the influence of cook-top surface temperature on CE by breaking down the results of the study reported herein into two sub-sections.

The first sub-section compares the test results for the 160°C and 200°C cases (i.e. the previously specified ASTM temperatures), which were performed on all five range hood tests units at one fixed mounting height. Next, the results for the three units that were tested at the additional 'Top Surface' temperature of 130°C (Fan 3, Fan 4 and Fan 5 only) are presented in a separate sub-section in order to analyze the effects of testing outside of previously specified ASTM temperature ranges.

In each sub-section presented herein, the influence of cook-top temperature on CE and CE repeatability/reproducibility is quantified by observing the changes in average CE, CE uncertainty (δ), standard deviation (σ) as well as the ΔCE, α, β and ε metrics presented previously. It should be noted that the average CE is a measure of the CE performance of a range hood under specific test conditions, δ represents the uncertainty in this CE measurement and σ represents the stability of this CE measurement during testing. Furthermore, ΔCE is a measure of the repeatability of CE tests performed back-to-back, α and β represent the reproducibility for CE tests performed at separate instances and ε the overall variation between tests performed multiple times.

Influence of changing ASTM specified cook-top temperature

The influence of lowering the ASTM specified cook-top temperature from 200°C to 160°C was investigated by adjusting all fans to a fixed mounting height, then performing two consecutive CE tests (i.e. Test 1 and Test 2) at the high and low speeds, and at both temperatures, before dismounting the fan. Next, the fan was re-mounted and a final CE test (i.e. Test 3) was performed at both speeds and both temperatures, as outlined in the previous experimental methods section. In all cases the range hood was tested twice at the highest speed setting, or high speed (HS), and two consecutive times at the lowest speed setting, or low speed (LS), before dismounting and then remounting for one final HS and LS test. All of the range hoods were tested at a fixed 27in. mounting height, aside from the OTR microwave that has a manufacturer specified mounting height range of 13-19in. For this sub-section, the OTR microwave was set to a fixed mounting height of 16in.

Effects on average CE and CE Uncertainty

The influence on average CE of changing the ASTM specified cook-top temperature from 200°C to 160°C is presented in Figure 24.

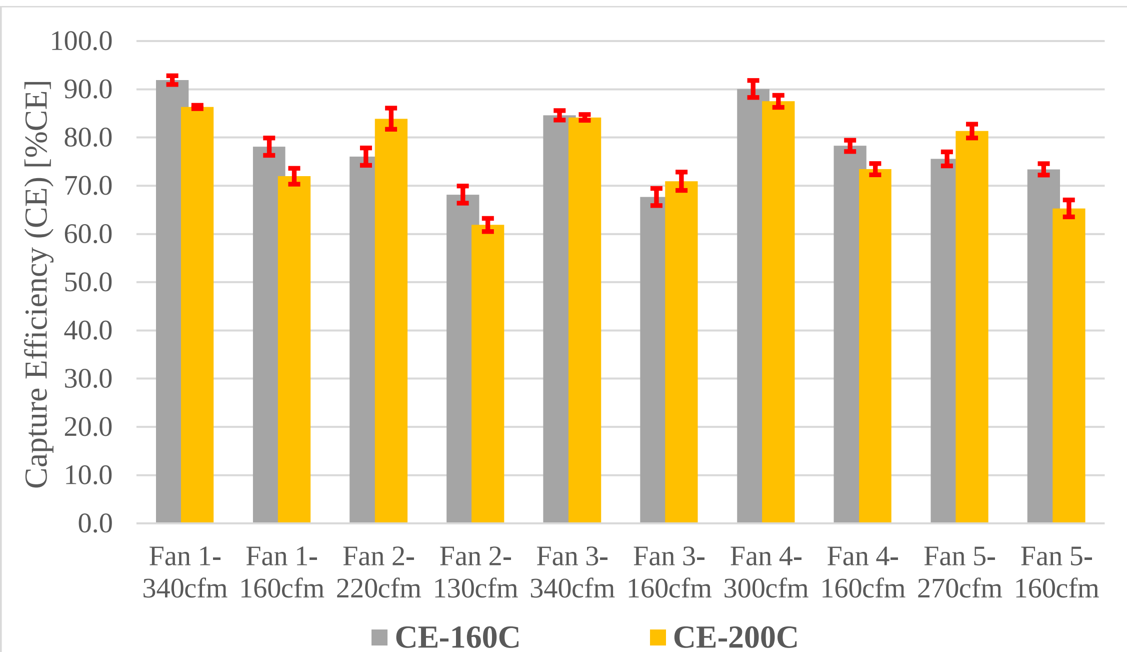


Figure 24: Influence of changing ASTM specified temperature on average CE. Error bars represent 2 standard deviations.

Figure 24 shows that for cases of varying temperatures within previously specified ASTM ranges, there is no uniform trend that can be observed across all fans. Only two out of the five fans, namely Fan 1 and Fan 4, show a consistent reduction in CE at higher surface temperatures for both high and low speeds. Thus, it can be concluded that the average CE does not show a pattern of increases or decreases with increasing surface temperature.

Furthermore, results showed that 30% of cases showed no significant change in CE when lowering the temperature within previously prescribed ASTM temperatures. Additionally, 50% of cases showed a significant increase in CE with an average increase of 6.2%CE and 20% of case showed a significant decrease in CE with an average value of 6.8%CE. Table 3 presents the aforementioned trends in a table format with up and down arrows representing increasing or decreasing CE, respectively, as the temperature is decreased 200˚C to 160˚C. Also shown are horizontal arrows that signify the CE change was within the measured variability for both tests (i.e. 200˚C and 160˚C tests) as measured using ±1 standard deviation (σ).

Table 3: Changes in CE for fans tested at fixed height

Fixed Height	From 200˚C to 160˚C			
	Low Speed		High Speed	
	Inc. or Dec.	δCE	Inc. or Dec.	δCE
Fan 1 - 27"	↑	**+6.1**	↑	**+5.6**
Fan 2 - 27"	↑	**+6.3**	↓	**-7.9**
Fan 3 - 27"	↔	**3.2**	↔	**0.4**
Fan 4 - 27"	↑	**+4.9**	↔	**2.6**
Fan 5 - 16"	↑	**+8.1**	↓	**-5.7**

Table 3 shows that 60% of cases showed a significant change in CE greater 5%CE when lowering temperature from 200C to 160C. It should be noted that some fans showed larger deviations in CE when changing the surface temperature, namely Fan 2 and Fan 5, as compared with Fan 3 that showed less deviation when varying surface temperature.

Additionally, all fans showed higher deviations at the low speed except Fan 2, which showed a higher deviation at the high speed, thus indicating surface temperature effects are dominant at lower speeds. The effects of changing the ASTM specified surface temperature on CE uncertainty (δ) are presented in Figure 25.

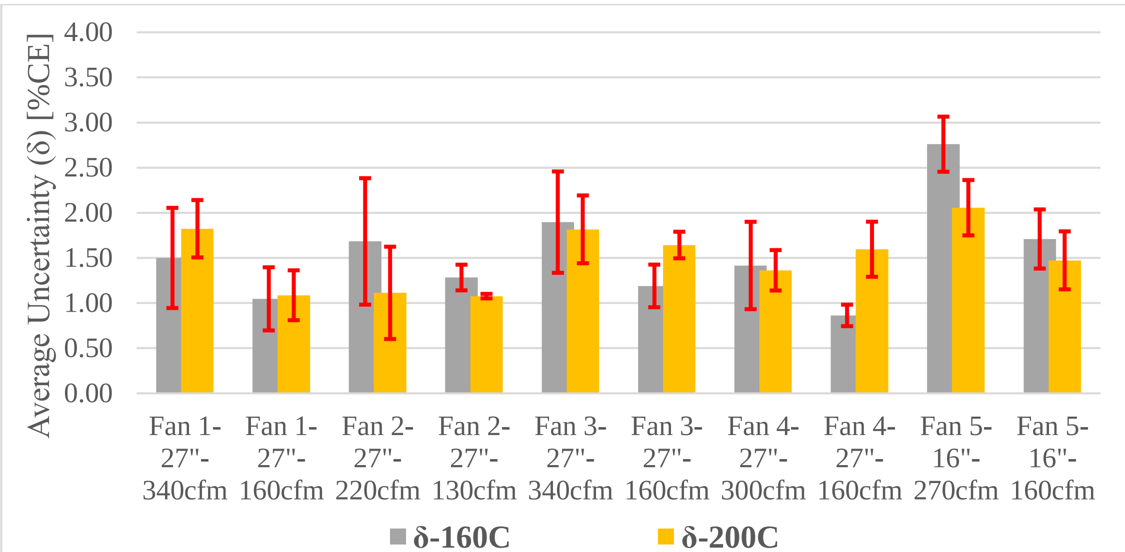


Figure 25: Influence of changing ASTM specified temperature on average uncertainty (δ). Error bars represent ±1 standard deviation.

Similar to the average CE, it can be observed in Figure 25 that reducing the surface temperature sometimes improves and sometimes worsens the uncertainty measurement. The range of uncertainties for the 200C cases was 1.08-2.06%CE with an average value of 1.51%CE. The range of uncertainties for the 160C cases was 0.86-2.76%CE with an average uncertainty of 1.54%CE. Only one of the test cases had an average uncertainty greater than 2.5%CE, namely the test performed for the OTR at 160C. It is believed that the high δ for the OTR is a consequence of the test fan having poor burner coverage and a high flowrate through a smaller grill, since the 200C case also shows a relatively higher δ. Furthermore, only 40% of cases showed a statistically significant difference in δ when varying cook-top surface temperature. The maximum discrepancy in δ was 0.76%CE and only 20% of cases showed a statistically significant difference in δ greater than 0.5%CE, indicating that the test procedure can confidently predict CE independent of surface temperature.

Therefore, since 60% of cases showed changes in CE greater than 5.0%CE, and the uncertainty was less than 2.5%CE for 95% of cases with an average value of 1.5%CE at both ASTM specified temperatures, it can be concluded that cook-top temperature influences the measured CE value but has no effect on CE uncertainty.

Effects on CE Repeatability

The influence of cook-top temperature on CE repeatability was determined by analyzing two different metrics, namely the standard deviation between the last 10 CE measurements of a specific test (σ) and the repeatability metric ΔCE defined as the difference between consecutive CE tests (i.e. those run before the range hood was dismounted and then remounted). Figure 26 shows the average σ value for all the fans tested at an intermediate height.

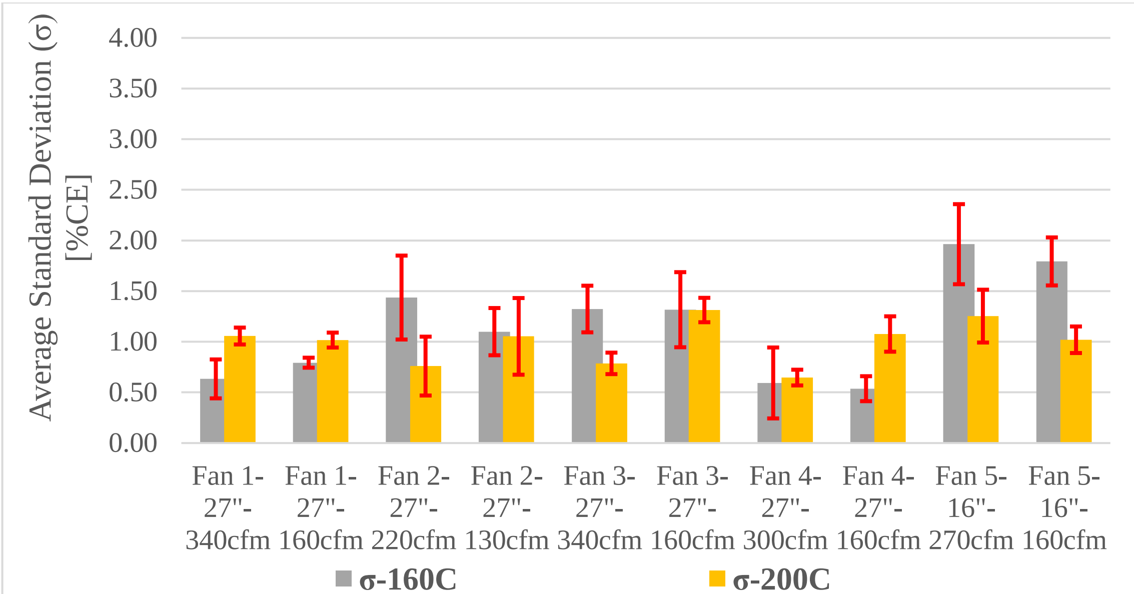


Figure 26: Average standard deviation (σ) for fans tested at intermediate height. Error bars represent ±1 standard deviation.

Figure 26 shows that all cases considered in this sub-section had an average standard deviation (σ) less than 2.0%CE. Although the results in Figure 26 show 60% of cases having statistically significant differences in the average σ value when varying surface temperature, all the cases had differences in σ of less than 1%CE and only 30% of cases had differences in σ greater than 0.6%CE. Since the average σ was less than 2.0%CE for all cases and the maximum discrepancy between σ values performed at different temperatures was less than 1.0%CE, it can be concluded that surface temperature has little to no effect on the variation between the 10 CE measurements gathered during a specific test (i.e. the standard deviation, σ). Figure 27 shows the absolute differences in CE tests (ΔCE) for tests performed at the previously specified ASTM temperatures.

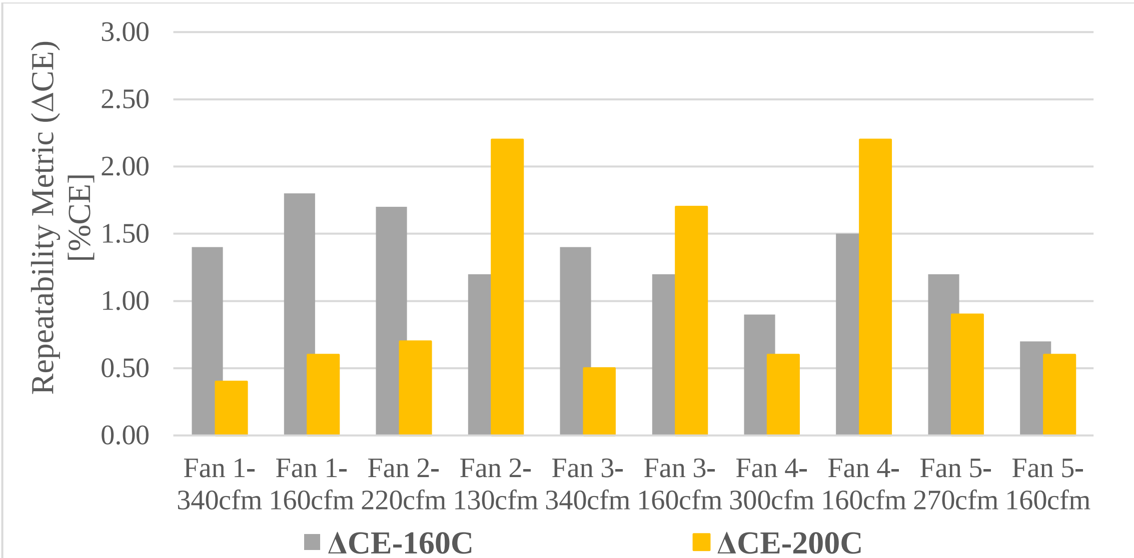


Figure 27: Repeatability Metric (ΔCE) showing absolute difference between CE Test 1 and 2

Figure 27 shows that ΔCE is always less than 2.5%CE and only two tests had a ΔCE value greater than 2.0%CE. Similar to uncertainty (δ) and standard deviation (σ), there is no consistent trend across all fans for ΔCE as a function of flowrate across both temperatures (i.e. ΔCE may increase with flowrate at 160C and decrease with flowrate at 200C, or vice versa). 40% of fans show ΔCE increasing with flowrate for both temperatures, 20% of fans show a decrease in ΔCE with increasing flowrate and 40% have opposite behaviors at the two temperatures.

Furthermore, depending on the range hood and speed setting, changes in the surface temperature can sometimes improve and sometimes worsen the repeatability. For 70% of cases, ΔCE is higher at 160C while 30% of cases show ΔCE to be higher at 200C. It should be noted that only 10% of cases showed a change in ΔCE greater than 1.0% when comparing 160C and 200C. Specifically, the difference between ΔCE at 160C and ΔCE at 200C had a range of 0.1%CE to 1.2%CE and an average value of 0.7%CE. Therefore, since the average uncertainty (δ) was 1.5%CE and the maximum difference in ΔCE between 200C and 160C is 1.2%CE, it can be concluded that surface temperature has little or no effect on CE repeatability as measured using ΔCE.

Effects on CE Reproducibility

The effects of cook-top temperature on CE reproducibility were investigated by analyzing the influence on the reproducibility metrics α and β, which were presented in an earlier section and require a mandatory dismount and re-mount. The reproducibility metric α plotted in Figure 28 is the absolute difference between CE Test 3 and the average of CE Test 1 and CE Test 2 (i.e. CE Avg.) as was shown earlier in Equation 10.

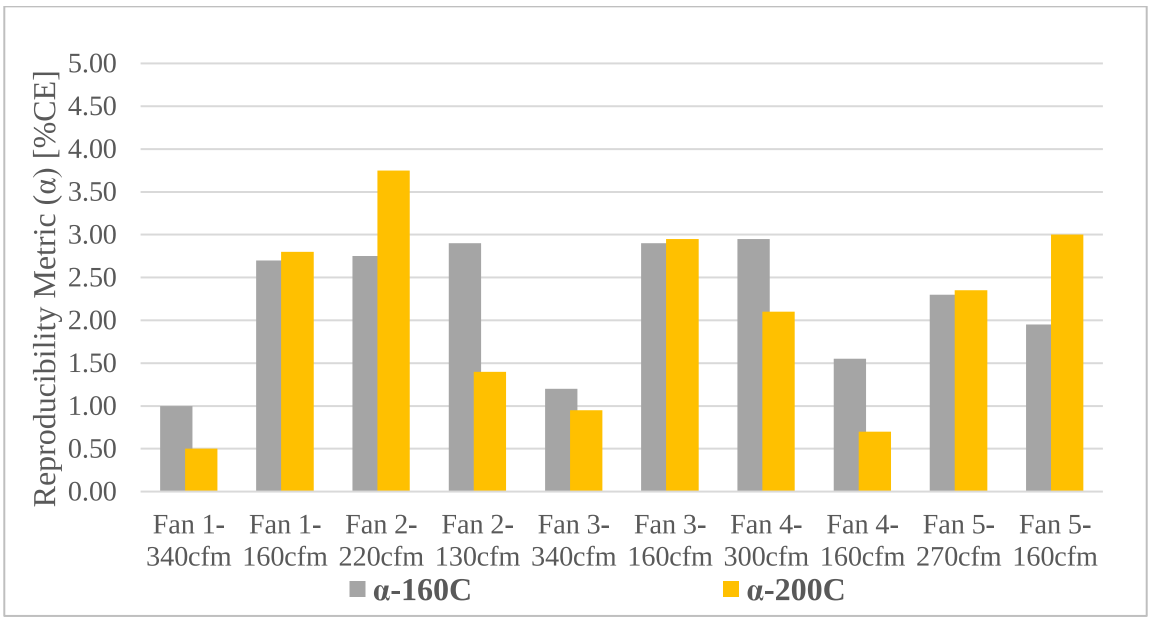


Figure 28: Reproducibility Metric, α, showing the absolute difference between CE Test 3 and CE Avg.

Figure 28 shows that all α values are less than 4.0%CE, regardless of cook-top temperature. 50% of cases showed that 160C has the highest α value, with values ranging from 1.00-2.95%CE and an average value of 2.22%CE and 50% of cases show α at 200C to be highest with a range of 0.50-3.75%CE and an average of 1.85%CE, while 33% of cases show that 200C has the highest α value, with a range of 0.70-3.00%CE and an average of 2.25%CE. Furthermore, the difference between α at 200C and 160C is 1.5%CE at worst, with an average value of 0.63%CE, indicating that the average discrepancy in α at 200C and α at 160C is within the expected uncertainty. Similar to the repeatability metrics σ and ΔCE presented in the previous section, α metric sometimes worsens and sometimes improves with decreasing temperature.

Furthermore, for 60% of the fans analyzed α shows the same increasing or decreasing trend with flowrate independent of temperature. However, this increasing/decreasing trend in α with flowrate can vary among fans (i.e. some fans show α increasing with flowrate and some show it decreasing with flowrate).

Investigation of the reproducibility metric β yielded similar findings to α with all β values being less than 5.0%CE. Figure 29 shows the results for the performance metric β for all cases analyzed in this sub-section.

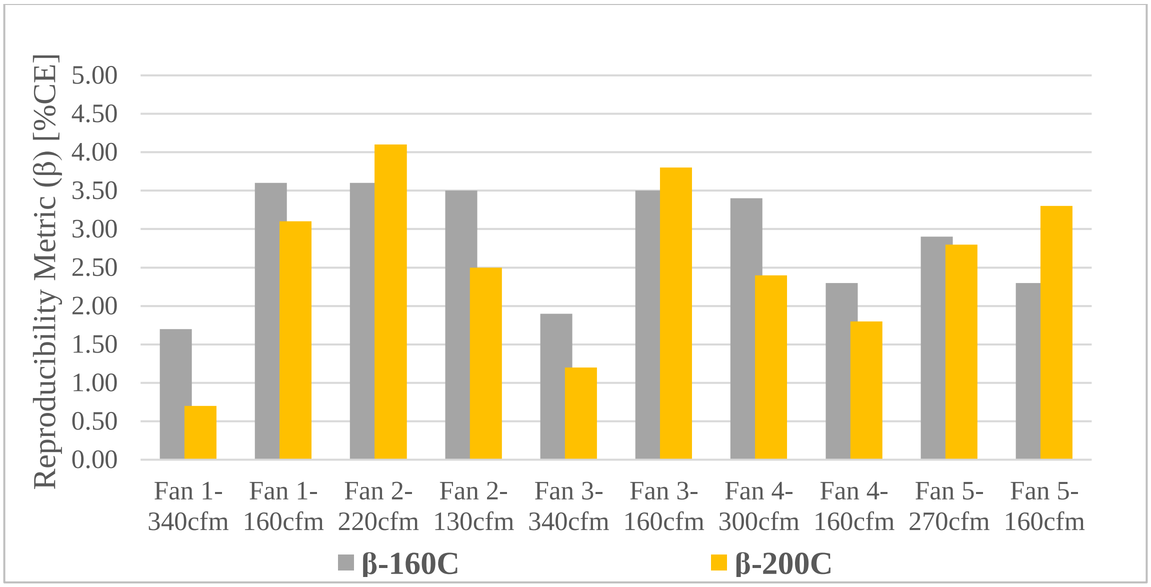


Figure 29: Reproducibility Metric (β) showing maximum absolute difference (CE Test 3 – CE Test 1 or CE Test 3 – CE Test 2)

Figure 29 shows the maximum difference between β at 160C versus β at 200C was 1.0%CE with an average difference of 0.66%CE (i.e. within typical uncertainty encountered in this section). When the β at 160C was greater than the β at 200C, the difference between the two values ranged from 0.1%CE to 1.0%CE with an average difference of 0.68%CE. Additionally, when the β at 200C was greater, the difference between the two values ranged from 0.1%CE to 1.0%CE with an average difference of 0.60%CE. Although varying the cook-top temperature can have an observable effect on the CE reproducibility graphs, since the average difference in β between the two temperatures was 0.66%CE and always than or equal to 1.0%CE, it can be concluded that cook-top temperature has little to no effect on CE reproducibility.

Similar to α, 80% of the fans show the reproducibility metric β has a constant increase or decrease with airflow rate independent of temperature. Another key observation is that in all cases using β to quantify reproducibility always yields higher values than α. This finding is important from an HVI/ASHRAE certification perspective as it gives users, manufacturers and test engineers insight on the expected ranges for different reproducibility metrics, and how the choice of metric can influence this range. Previous studies on burner placement showed that front burners produce a larger range of CE values, and therefore ASTM-E3087.18 specifies front burner placement (Kim, 2018). Based on this same logic, it may be ideal to use β as the primary reproducibility metric for HVI/ASHRAE certification procedures, as β yields a higher range of reproducibility values.

Effects on CE Variability

The effects of cook-top temperature on CE variability were analyzed by comparing the influence of cook-top temperature on the coefficient of variation (ε), which normalizes the variation encountered by a group of repeated CE tests by dividing the average CE of the three tests by the standard deviation between the tests as described earlier. Figure 30 presents the different values for ε observed in this sub-section.

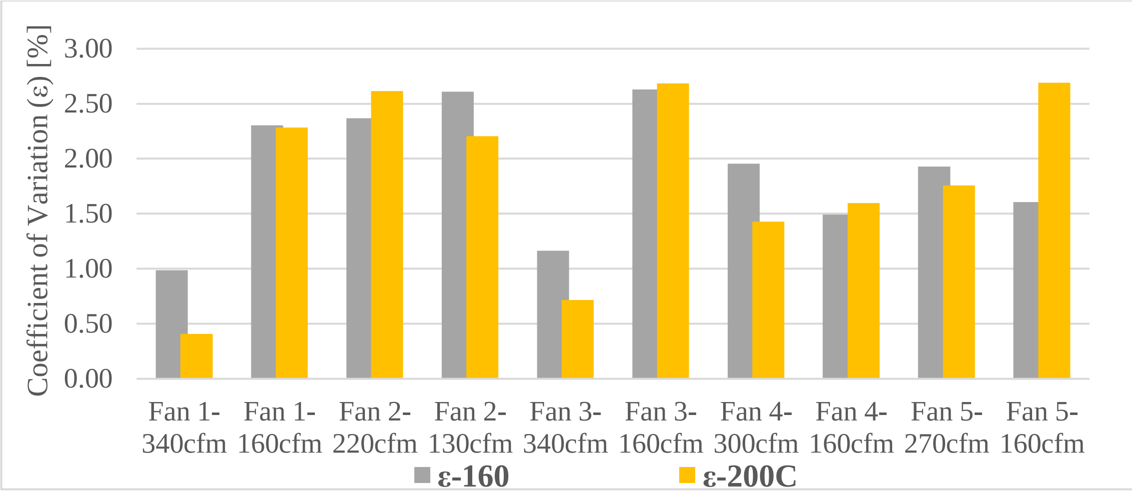


Figure 30: Variability Metric (ε) showing coefficient of variation (%) for all fans tested at ASTM prescribed temperatures

Figure 30 shows that for all fans tested in this section, ε was always less than 3% and less than 2.5% for 75% of the tests, which indicates that CE shows minimal variation independent of surface temperature. At 160C, 70% of the cases showed a higher variability with ε varying from 0.99% to 2.63% and having an average value of 1.91%. At 200C, 30% of cases showed a higher ε with values ranging from 0.41% to 2.69% and an average value of 1.84%. Furthermore, only one of the cases had a difference in ε greater than 1% when changing the temperature from 200C to 160C, which was the OTR microwave with poor burner coverage and small grill/filter openings. Therefore, it can be concluded that CE is not expected to exhibit different variability patterns when changing the cook-top temperature (i.e. the variation between tests at 200C is comparable to the variation at 160C).

Influence of varying cook-top temperature outside of ASTM specified ranges (i.e. 130°C)

The influence of varying the cook-top temperature outside of currently and previously specified ASTM ranges was also investigated for three of the range hoods tested. Once again, all range hoods were tested two consecutive times at the high speed (HS), then twice at the low speed (LS) setting, before dismounting and remounting for one final HS and LS test. Two of the range hoods were tested at a fixed 27in. mounting height and the OTR microwave was set to a fixed mounting height of 16in.

Effects on Average CE and CE uncertainty

The effects on CE of varying the cook-top temperature outside of the range specified by the ASTM is shown in Figure 31.

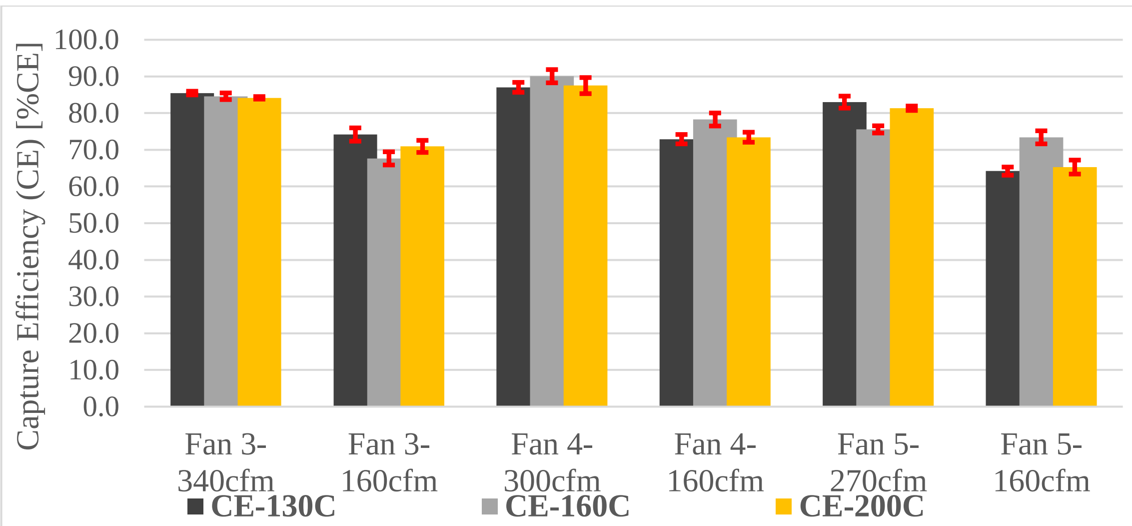


Figure 31: Average CE for Fans tested outside ASTM specified temperatures. Error bars represent ±1 standard deviation.

Focusing on Figure 31, out of six cases and 18 possible temperature comparisons, 50% of comparisons show a significant difference in CE between temperatures, as compared to 70% for the ten cases and twenty possible comparisons presented in the previous section. An interesting trend that can be observed in **Figure 11** is that 5 out of 6 fans show a parabolic trend for CE with increasing temperature for these three temperatures (i.e. CE rises and then drops as temperature increases, or vice versa). Furthermore, no fans showed a statistically significant distinction in CE between all temperatures; rather,

Figure 31 shows that one of the three CE values is significantly different from the other two CE values, which are similar to each other. In summary, these results indicate that testing outside of ASTM prescribed temperatures gives comparable CE values to testing within ASTM prescribed temperatures.

Table 4 shows the differences in CE tested at different temperatures (δCE) for all cases compared in this sub-section. The average variation in CE when changing cook-top temperature was 3.7%CE and the maximum variation was 9.2%CE, which was the OTR operating at low speed. Excluding the OTR microwave, the maximum variation in CE is 6.5%CE. Furthermore, 67% of cases showed variations in CE less than 5.0%CE (i.e. ±2.5%CE) or 83% of cases when excluding the OTR microwave. It should be noted that 94% of cases analyzed in this entire study had an uncertainty less than or equal to 2.5%CE indicating that most of the variations in CE were within the typical ranges of CE uncertainty and thus not directly resulting from changes in cook-top surface temperature

Table 4: Differences in CE (δCE) for fans tested outside of ASTM specified cook-top temperature

Outside ASTM Range	200˚C → 160˚C				160˚C → 130˚C				200˚C → 130˚C			
	LS		HS		LS		HS		LS		HS	
	Inc or dec	δCE	Inc or dec	δCE	Inc or dec	δCE	Inc or dec	δCE	Inc or dec	δCE	Inc or dec	δCE
Fan 3 - 27"	↔	**3.4**	↔	**0.5**	↑	**+6.5**	↔	**0.9**	↔	**3.2**	↑	**+1.3**
Fan 4 - 27"	↑	**+4.9**	↔	**2.6**	↓	**-5.4**	↔	**3.1**	↔	**0.5**	↔	**0.5**
Fan 5 - 16"	↑	**+8.3**	↓	**-5.4**	↓	**-9.2**	↑	**+7.4**	↔	**1.1**	↔	**1.7**

When changing temperature within the ASTM prescribed range (i.e. from 200C to 160C), 50% of cases presented in this sub-section showed a significant change in CE. Furthermore, changing temperatures from 160C to 130C showed 67% of cases having a significant change in CE and changing from 200C to 130C showed 17% of cases had a significant change in CE. Thus, it can be concluded that testing outside of temperatures prescribed by ASTM does not have any more of a significant impact on CE than testing within the temperatures prescribed by ASTM.

Additionally, the effects of changing the cook-top temperature to temperatures outside of the ASTM specified range on CE uncertainty (δ) were also investigated. The results of varying the cook-top temperature outside of the ASTM specified range are presented in Figure 32.

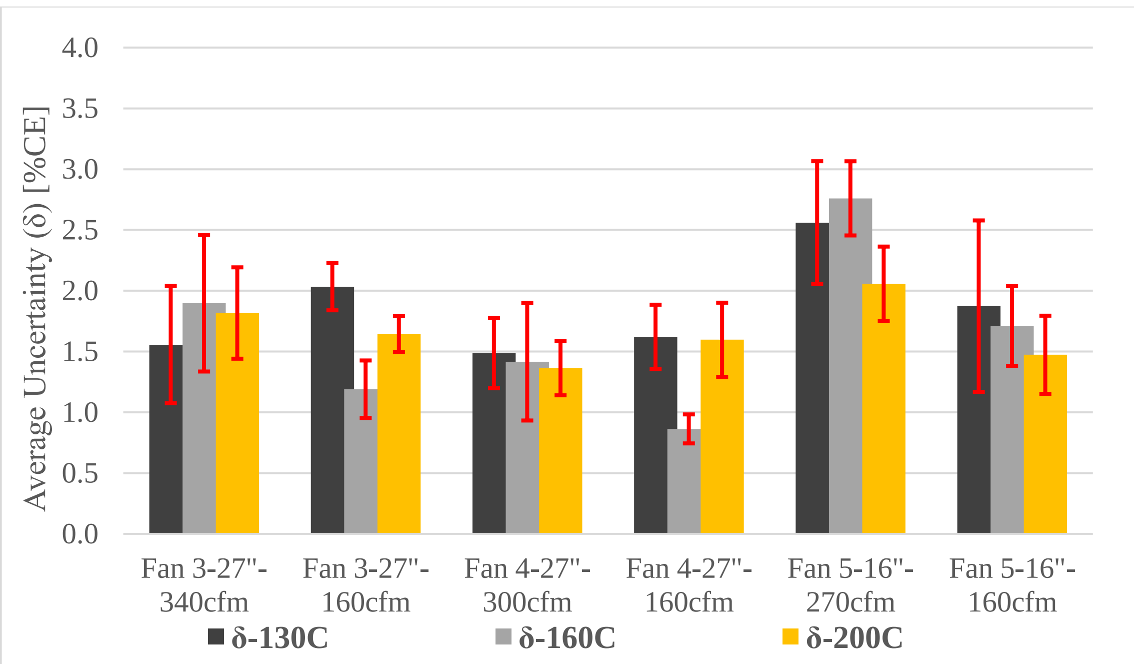


Figure 32: Average Uncertainty (δ) for Fans tested outside ASTM specified temperatures. Error bars represent ±1 standard deviation.

Figure 32 shows that only 33% of comparisons showed a statistically significant variation in δ when varying cook-top temperature. Furthermore, the deviation in δ when varying cook-top surface temperature for a specific fan was always less than 1.0%CE. Thus, it can be concluded that uncertainty in CE is unaffected by cook-top temperatures, even at temperatures outside of those previously prescribed by the ASTM.

Effects on CE Repeatability

The influence on CE repeatability of varying the cook-top temperature outside of the ASTM specified range was determined by analyzing the standard deviation between the last 10 CE measurements of a specific tests (σ) and the repeatability metric ΔCE defined as the difference between consecutive CE tests for each specific case. Figure 33 shows the average σ value for fans tested outside of previously specified ASTM ranges.

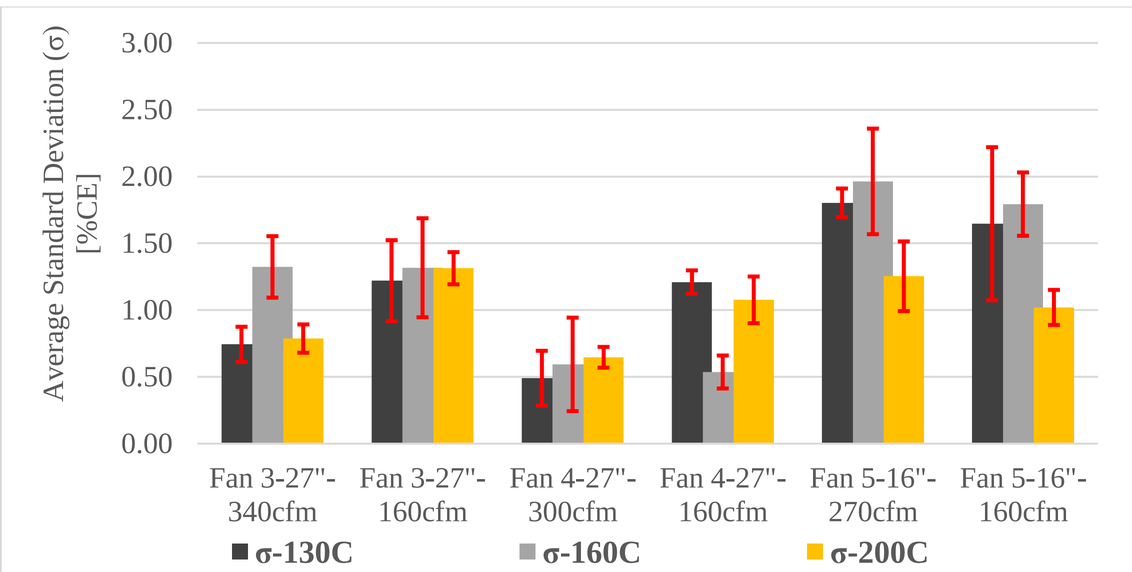


Figure 33: Average Standard Deviation (σ) for Fans tested outside ASTM specified temperatures. Error bars represent ±1 standard deviation.

Figure 33 shows that the average value for σ is less than 1.5%CE for 78% of cases, or 100% of cases excluding the OTR microwave, and always less than 2.0%CE. For the six fans and 18 possible comparisons presented in this sub-section, 39% of comparisons showed statistically significant difference in σ when varying the cook-top temperature. However, only one of the comparisons had a statistically significant difference in σ greater than 0.75%CE, namely the OTR microwave at low speed. Otherwise, all statistically significant differences in σ were less than 0.70%CE indicating that repeatability of CE is unaffected by cook-top temperatures outside of the ASTM prescribed ranges.

The effects on CE repeatability when varying the cook-top temperature outside of the ASTM specified range were also investigated by analyzing the ΔCE metric, which shows the difference between repeat CE tests (i.e. those tests performed without dismounting and re-mounting the range hood). The ΔCE values for fans tested outside of the ASTM specified range are shown in Figure 34.

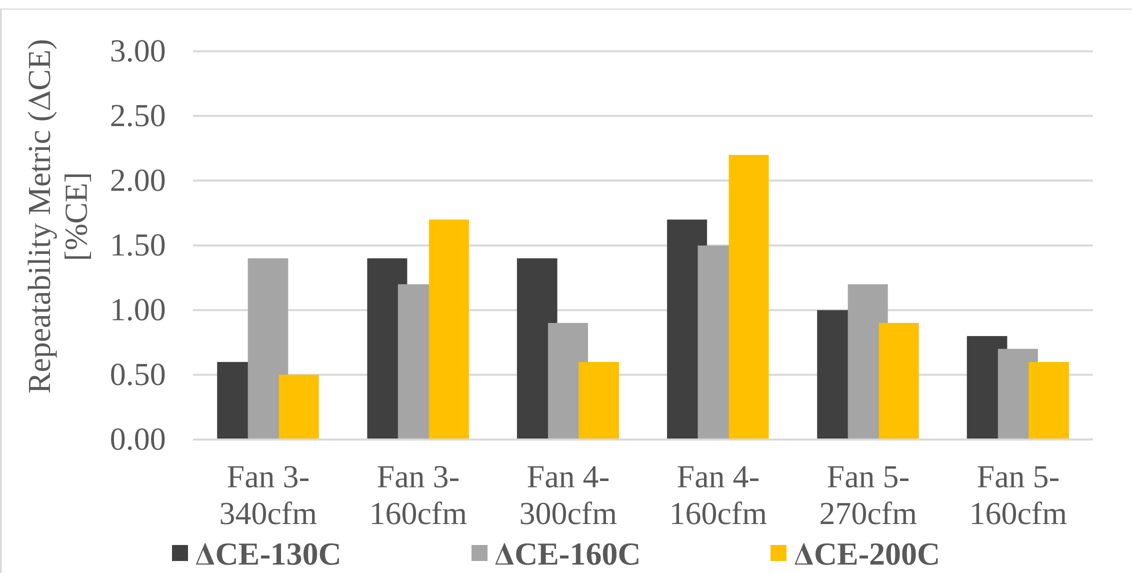


Figure 34: Repeatability metric (ΔCE) for fans tested outside ASTM specified temperatures.

Figure 34 shows that for all cases considered in this sub-section, the maximum value for ΔCE was always less than 2.5%CE and less than 2.0%CE for 94% of cases. 33% of cases showed 130C has the highest value for ΔCE, 33% of cases showed 160C had the highest value for ΔCE and 33% of cases showed 200C had the highest value for ΔCE. The values for ΔCE ranged from 0.6-1.7%CE for the 130C cases, 0.7-1.5%CE for the 160C cases and 0.5-2.2%CE for the 200C cases, indicating there is not much variation in repeatability when comparing different temperatures.

Furthermore, when comparing the different cook-top temperatures for a specific case, the largest discrepancy between ΔCE across different temperatures is 0.9%CE, which is within the typical uncertainty values encountered in this study. These results further indicate that repeatability, as quantified using the ΔCE metric, is un-influenced by cook-top temperature, even at temperatures outside of the ASTM prescribed ranges.

Effects on CE Reproducibility

The effects on CE reproducibility when varying the cook-top temperature outside of the ASTM specified range were investigated by analyzing the reproducibility metrics α and β, which consider a mandatory dismount/re-mount between tests. The reproducibility metric α is presented in Figure 35 and shows the absolute difference between CE Test 3 (performed after dismounting and then re-mounting) and the average of CE Test 1 and CE Test 2 (performed back-to-back).

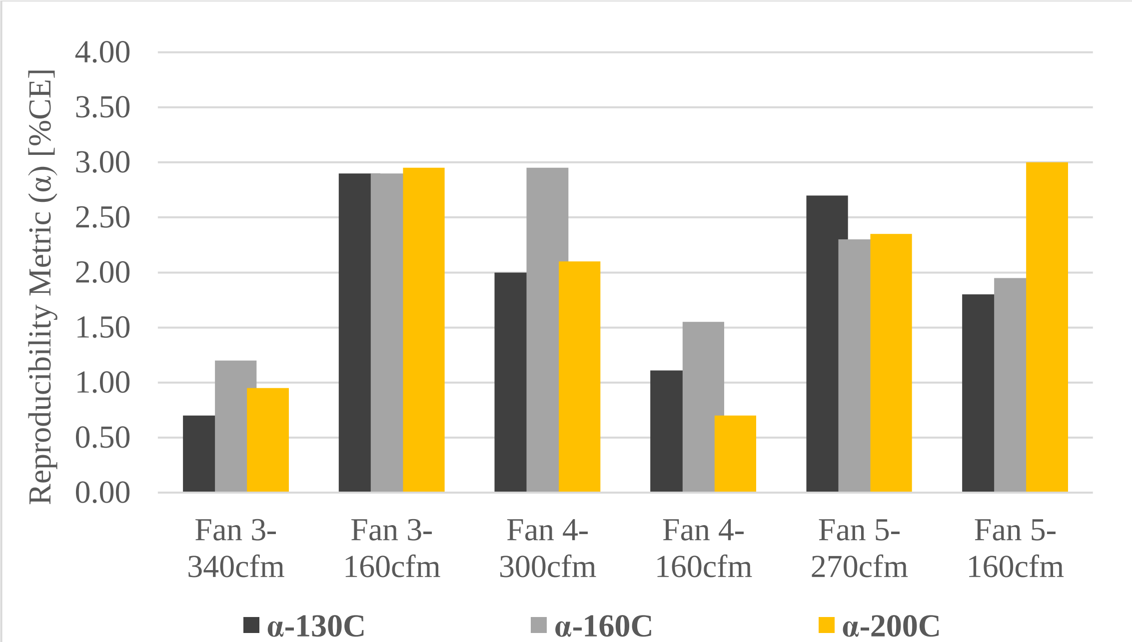


Figure 35: Reproducibility Metric (α) for fans tested outside ASTM specified temperatures

Figure 35 shows that for all cases α is less than or equal to 3.0%CE indicating acceptable reproducibility that is within the maximum uncertainty experienced in this study (i.e. 5.0%CE or ±2.5%CE). 50% of cases showed that 160C has the highest α value, with values ranging from 1.20-2.95%CE and an average value of 2.14%CE. Additionally, 17% of cases show α at 130C to be highest with a range of 0.70-2.90%CE and an average of 1.85%CE, while 33% of cases show that 200C has the highest α value, with a range of 0.70-3.00%CE and an average of 2.01%CE. From these results, it can be concluded that there is no clear trend between CE reproducibility (α) and cook-top temperatures outside of ASTM prescribed ranges.

The largest variation in α across temperatures was 1.2%CE, which was experienced by Fan 5 (OTR) at low speed, indicating that all variations in α across temperatures are within the typical uncertainties experienced in this study; therefore, cook-top temperature has no detectable effect on CE reproducibility. However, fans with less burner coverage are more susceptible to changes in cook-top temperature as indicated by the OTR Fan 5 at low speed.

It can also be observed in Figure 35, that each fan shows the same increase/decrease in α with increasing flowrate for all temperatures tested. However, there is one anomaly, which is Fan 5 at 200C that shows a decrease in the reproducibility metric α with increasing flowrate, whereas 160C and 130C show α increasing with flowrate.

As another means to quantify reproducibility, Figure 36 presents the β metric presented previously in Equation 11. Figure 36 shows that all β values are less than 4.0%CE with only 11% of tests having a β value greater than 3.5%CE. β shows a similar trend on reproducibility as α with β increasing or decreasing with flowrate for all temperatures, except for Fan 5 at 200C. Similar to α, β can either increase or decrease depending on the fan type. Also, once again, β has a higher maximum value and larger range than α indicating that it may be preferred for use in an HVI/ASHRAE certification program

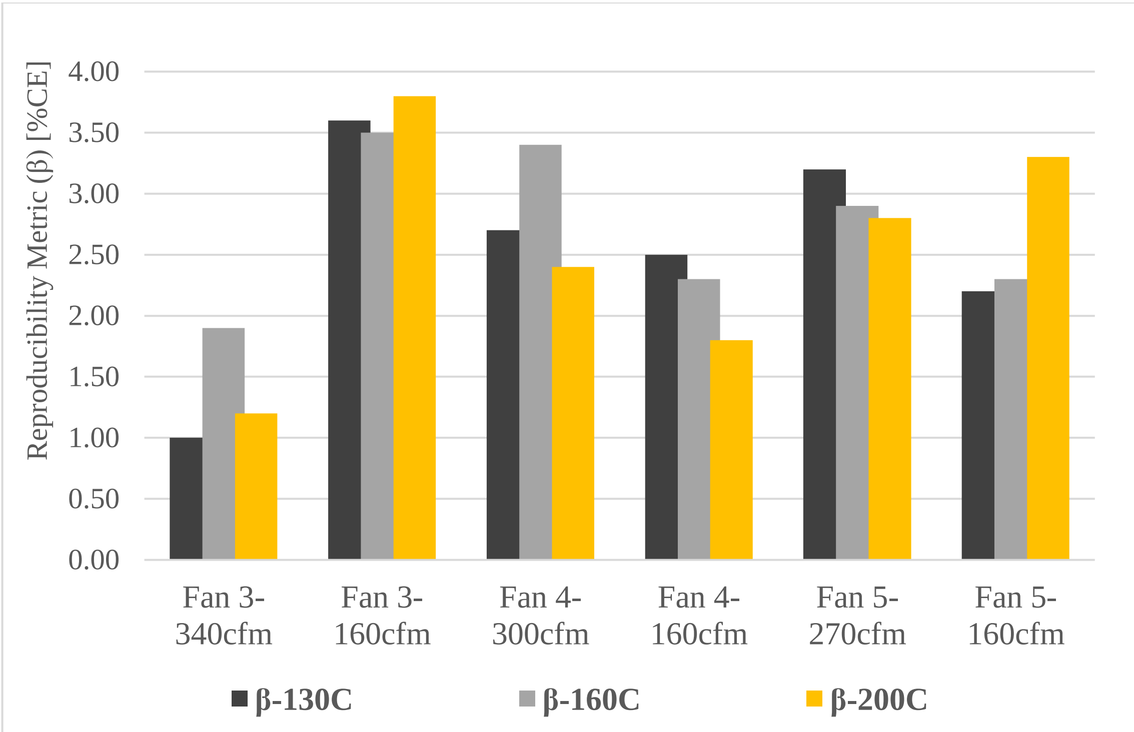


Figure 36: Reproducibility Metric (β) for fans tested outside ASTM specified temperatures

Referring to Figure 36, 33% of cases show 130C to have the highest β value with values ranging from 1.00-3.60%CE, 33% of cases show 160C to have the highest value for β with values ranging from 1.90-3.50%CE and 33% of cases show 200C to have the highest value for β with a range of 1.20-3.80%CE. Additionally, the average values for the reproducibility metric β at 130C, 160C and 200C are 2.53%CE, 2.71%CE and 2.55%CE, respectively. Thus, it can be concluded when performing CE testing in accordance with ASTM-E3087.18 outside of the ASTM prescribed temperatures, namely at 130C, that there is no more of a significant effect on reproducibility than there is at the other two temperatures.

Effects on CE Variability

The effects on CE variability when using cook-top temperatures outside of the ASTM specified range were analyzed using the coefficient of variation (ε). Figure 37 presents the different values of ε for the cases considered in this sub-section.

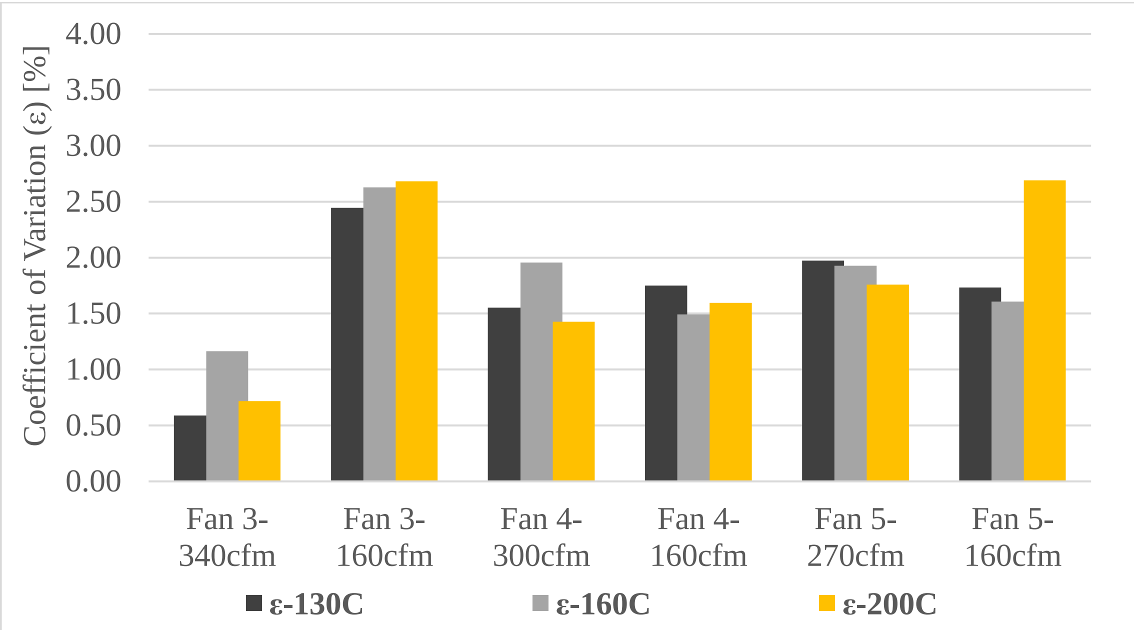


Figure 37: Variability Metric (ε) showing coefficient of variation (%) for fans tested outside ASTM specified temperature

Figure 37 shows that in all cases, the coefficient of variation ε is always less than 3.0% and less than 2.5% for 83% of cases. In general, 33% of cases showed 130C to have the highest variation with a range of 0.59-2.45% for ε, 33% of cases showed 160C to have the highest variation with a range of 1.16-2.63% for ε and 33% of cases showed 200C to have the highest variation with a range of 0.72-2.69% for ε. Thus, showing that none of the cook-top temperatures exhibited significantly higher variability across the fans tested. Additionally, the average variability (ε) for 130C, 160C and 200C was 1.67%, 1.79% and 1.81%, respectively, indicating a maximum difference in average ε of 0.14%

or an 8% relative difference. Therefore, based on the minimal discrepancy in average ε across all temperatures, it can be concluded that cook-top temperature has little to no effect on CE variability even at cook-top temperatures outside of the ASTM prescribed ranges.

When comparing the ε values across temperatures for a specific case, the maximum difference in ε was 1.08%CE for Fan 5, the OTR fan, at low speed. Therefore, since the differences in variability metric (ε) across the varying temperatures was within the typical uncertainties experienced in this study, it can be concluded that cook-top temperature has no effect on CE variability, even at temperatures outside of the ASTM prescribed ranges.

Summary

Recently a test procedure for determining capture efficiency (CE) of residential wall-mounted range hoods was developed, namely ASTM-E3087.18. The test procedure involves building a simulated kitchen with necessary cabinetry, counter-tops and portable electric burners to mimic a stove-top. Atop the electric burners are tracer-gas emitter that are used to inject CO2, which simulates cooking contaminants, into the chamber and then measuring the CO2 at various points in the chamber to determine CE. Although the test procedure was finalized in 2018, it was initially released in 2017 and revised within the first year to modify the temperature requirements of the simulated cook-top. Specifically, the cook-top temperature was changed from 200C to 160C. In this study a capture efficiency (CE) test chamber built in accordance with ASTM-E3087.18 was used to conduct several experiments that investigate the effects of this cook-top temperature change on CE and CE uncertainty, as well as CE repeatability, reproducibility and variability. Additionally, the effects of CE testing at cook-top temperatures outside of previously specified ASTM ranges were also investigated.

In summary, it was found that temperature had a significant effect on the CE measurement, changing the average CE by as much as 9.2%CE, but did not seem to influence CE uncertainty or repeatability as much. When changing the cook-top temperature from 200C to 160C, 70% of tests showed a significant change in average CE compared with 50% of cases that incorporate temperatures outside of the ASTM prescribed range (i.e. 130C). No fans showed a statistically significant difference in CE across all temperatures; rather, only one of the three CE values is significantly different from the other two CE values, which are similar to each other. Thus, it can be concluded that testing outside of ASTM prescribed temperatures gives comparable CE values to testing within ASTM prescribed temperatures. Some fans showed larger deviations in CE with changing surface temperature than others and only two out of five fans, showed a consistent change in CE with surface temperature at both high and low speeds. Thus, it can be concluded that the average CE does not show a consistent increase or decrease with varying temperature. Furthermore, four out of five fans showed a larger discrepancy in CE due to temperature changes at the lower speeds, indicating surface temperature effects are dominant at lower speeds.

The uncertainty in CE (δ) was always less than 3.0%CE and greater than 2.5%CE for only one case, namely the OTR Fan 5 at high speed, indicating a high level of confidence in the CE measurements. The high uncertainty for Fan 5 is a consequence of the OTR having poor burner coverage and a high flowrate through a smaller opening (i.e. smaller grill/filter than the other range hoods). Reducing the cook-top temperature from 200C to 160C was found to sometimes improve and sometimes worsen the uncertainty measurement depending on the fan. When varying the temperature outside of the ASTM prescribed range, 33% of the temperature comparisons showed a significantly different δ, compared with 40% of the comparisons performed within the ASTM prescribed ranges. However, the maximum difference in δ when varying cook-top temperature was always less than 1.0%CE, thus indicating that the effects of cook-top temperature on CE uncertainty measurements are minor.

Repeatability was determined by analyzing the standard deviation (σ) between the last 10 CE measurements taken during a test and the absolute difference between consecutive CE tests (ΔCE). Results showed that the average value for σ was always less than 2.0%CE for all cases, and ΔCE was always less than 2.5%CE. Discrepancies in repeatability across different temperatures were within the range of typically experienced CE uncertainty, with a maximum discrepancy of 0.8%CE for σ and 1.2%CE for ΔCE. Thus, it can be concluded that surface temperature has little to no effect on CE repeatability as indicated by σ and ΔCE.

The effects of cook-top temperature on CE reproducibility were investigated by analyzing the influence on the reproducibility metrics α and β, which require a mandatory dismount and re-mount of the range hood. All α values were less than 4.0%CE, regardless of cook-top temperature, and only one α value was greater than 3.0%CE. Furthermore, all β values were less than 5.0%CE and only one tests had a β

value greater than 4.0%CE. A key observation made in this study is that in all cases using β to quantify reproducibility always yielded higher values than α. This finding is important from an HVI/ASHRAE certification perspective because previous studies on burner placement showed front burners to give a larger range of CE values, and therefore ASTM-E3087.18 specifies front burner placement (Kim, 2018). By that same logic, it may be ideal to use β as the primary reproducibility metric for HVI/ASHRAE certification procedures, as β yields a higher range of reproducibility values.

When varying the cook-top temperature, the maximum discrepancy in α was 1.5%CE and 1.0%CE for β. Additionally, for 60% of the fans analyzed the α metric always shows the same trend with flowrate independent of temperature (i.e. increases or decreases with flowrate regardless of cook-top temperature). Furthermore, β behaves similar to α in that 80% of the fans show that reproducibility has a constant increase or decrease with airflow rate independent of temperature However, the trend increase/decrease in α/ β with flowrate can vary between fans (i.e. some fans show α increasing with flowrate and some fans show it decreasing with flowrate). Closer analysis of β, the higher reproducibility metric, showed that 33% of cases had the highest β at 130C (range of 1.00-3.60%CE), 33% of cases had the highest β 160C (range of 1.90-3.50%CE) and 33% of cases had the highest β at 200C (range of 1.20-3.80%CE). Additionally, the average values for the reproducibility metric β at 130C, 160C and 200C are 2.53%CE, 2.71%CE and 2.55%CE, respectively. Thus, it can be concluded when performing CE testing in accordance with ASTM-E3087.18 outside of the ASTM prescribed temperatures, namely at 130C, that there is no more of a significant effect on reproducibility than there is at the other two temperatures

The effects of changing cook-top temperature on variability were investigated by analyzing the coefficient of variation (ε) between multiple CE tests. All cases showed an ε value less than 3.0% and 19% of tests had an ε value less than 2.5%. In general, 33% of cases showed 130C to have the highest variation with a range of 0.59-2.45% for ε, 33% of cases showed 160C to have the highest variation with a range of 1.16-2.63% for ε and 33% of cases showed 200C to have the highest variation with a range of 0.72-2.69% for ε. Thus, showing that none of the cook-top temperatures exhibited significantly higher variability across the fans tested. The average variability (ε) for 130C, 160C and 200C was 1.67%, 1.79% and 1.81%, respectively, indicating a maximum difference in average ε of 0.14% or an 8% relative difference. Based on a 0.14% maximum discrepancy in average ε across all temperatures, it was concluded that cook-top temperature has little to no effect on CE variability even at cook-top temperatures outside of the ASTM prescribed ranges.

As a final note, some fans were found to have higher uncertainty than others due to their inherent design and geometry (i.e. poor burner coverage, smaller grill/filter openings, etc.). Additionally, the OTR microwave was found to be more susceptible to variations in CE when changing temperatures (i.e. different variability performance at different temperatures). Thus, indicating temperature effects are more dominant for fans with poor burner coverage. It is possible that future HVI/ASHRAE certifications specify different acceptability criteria for the CE uncertainty and repeatability of range hoods with poor burner coverage (i.e. OTR microwaves), as results showed these fans were more susceptible to changes in temperature, specifically at higher flowrates.

CHAPTER VI

THE EFFECTS OF RANGE HOOD MOUNTING HEIGHT ON CAPTURE EFFICIENCY

Overview

Recently, ASTME-3087.18 released in 2017 underwent a revision in which the minimum mounting height requirement of 0.5m was removed. Specifically, in 2018 the standard was revised to remove the mounting height requirement in order to allow for a wider range of testing; however, it is not clear whether the effects of mounting height on CE were fully investigated prior to this change. Previous CE studies have investigated some mounting height effects by analyzing two specific mounting heights; however, none of these studies abide strictly to the test procedure specified in ASTM-E3087.18. Additionally, none of these studies emphasized the effects of mounting height on CE repeatability, uncertainty or variability; that is, the intent behind using multiple heights is not clear other than the fact that it increases the number of unique test scenarios (Walker, 2016) or based on manufacturer recommended heights (Kim, 2017 and Singer, 2011). It should be noted that Kim et. al. performed CE testing on just over 70 test scenarios involving varying heights, but only about 25% were performed in accordance with ASTM-E3087.18 (i.e. proper emitter design, tracer gas injection rate, etc.). In fact, it is not possible to determine whether the tracer gas emitters used by Kim et. al. were positioned in accordance with ASTM-E3087.18, as they were placed directly on top of a stove top rather than being portable and having the capability to be moved to different positions, depending on range hood widths, as specified by the ASTM.

Finally, since all previous studies on CE focused on only two mounting heights, and three points are required to draw a curve, there is a need to thoroughly investigate how mounting height influences CE by going beyond just two mounting heights.

In the study reported herein, CE testing was performed on 6 traditional under the cabinet (UTC) range hoods with equivalent widths of 30 in. Each range hood was tested at both the high speed (HS) and low speed (LS) for a total of 12 range hood configurations (i.e. unique combinations of range hood and speed). Additionally, each range hood configuration was tested at three different mounting heights, namely, 24in., 27in. and 30in, for a total of 36 unique test scenarios (i.e. unique combination of range hood, mounting height and speed). Finally, three CE tests were performed at each of these unique test scenarios for a total of 108 tests. Specifically, each range hood was tested three times with two of these tests being performed back-to-back without altering the test set-up and the final test occurring after a dismount/remount of the range hood. It should be noted that the mandatory dismount/re-mount during the test cycle is to observe how mounting height influences not only CE, but also its repeatability and reproducibility. It should be noted that a large portion of this chapter will be submitted for publication in the Science and Technology of the Built Environment (STBE) academic journal.

Problem Statement

The objective of this study is to identify, quantify and evaluate how changing the range hood mounting height affects measured values of CE. Previous studies have shown that the mounting height of the range hood can affect the perceived CE performance (Kim, 2017 and Walker, 2016); however, for both studies, the variations in height are only limited to two different heights and the test procedures used did not strictly adhere to the ASTM guidelines. Therefore, there is a need for a thorough investigation of the mounting height effects on CE in order to verify the accuracy and reliability of CE measurements at varying heights. An additional question that needs addressing is whether there is an optimum mounting height at which CE performance is optimized. Furthermore, in line with studying the effects of mounting height on CE, this study also investigates the effect of mounting height on CE repeatability and reproducibility (i.e. variations in calculated CE values for repeated tests) and whether there or not there is an optimum mounting height at which variations between repeat CE tests are minimized.

Experimental Methods

Test Facility

Testing of all range hoods reported herein was performed by using the aforementioned test chamber that was designed and built at the RELLIS Energy Efficiency Laboratory (REEL) at Texas A&M University. Of special note, this facility is the first built from the ground up at a public institution by following the guidelines of the recently published ASTM-E3087.18 Standard. A second facility at LBNL that meets ASTM standard guidelines was built even earlier, but it was built prior to the release of the standard, and in fact it was used to develop the original standard (Kim, 2018).

The test chamber used herein has dimensions of 4m x 5m (13.1ft x 16.5ft) with a ceiling height of 3m (10ft). The ceiling was built slightly higher than the 2.5m specified by the ASTM in order to allow for future testing of island range hoods that require higher mounting heights. It should be noted that the higher ceiling was supported by a number of organizations that participated in development of the original standard with the idea that the higher ceiling is not expected to affect the CE measurement. The chamber has a leakage rate of 1.7 ACH corresponding to 50 Pa, which is less than the 2.5 ACH specified by ASTM. The exhaust duct was built in accordance with ASTM-E3087.18 and has a leakage rate of 1.3 L/s (2.7 cfm) at 25 Pa, which is less than the ASTM specified value of 2.5 L/s at 25 Pa.

Airflow through the exhaust duct is measured by using a venturi tube built in accordance with the International Standard Organization (ISO) Standard ISO5167-4 for measurement of fluid flow by means of a pressure differential device. As detailed in Appendix E, the venturi tube has an uncertainty of 3.5% of the measured airflow, which is less than the ASTM-E3087.18 required value of 5% or 2.5 L/s (whichever is greater).

Test Procedure

A uniform test procedure identical to that used in the previous chapter was applied to all range hood tests performed in support of this study of mounting height effects on CE. The test procedure followed involved testing each range hood three times, at their respective high/low speeds and at three different mounting heights. Two of the three tests were performed consecutively (CE 1 and CE 2) in accordance with ASTM-E3087.18 to observe the effects of mounting height on CE repeatability (i.e. difference between tests run consecutively). Next, the mounting height of the range hood was changed before another set of consecutive tests were ran (CE 1 and CE 2). After performing two consecutive tests at each mounting height, the range hood was dismounted/re-mounted and tested again (CE 3) at each of the various mounting heights to observe the effects of mounting height on CE reproducibility. In all tests performed, specific attention was given to the trend of CE with time to ensure a steady-state CE was achieved. The test procedure for one of the hoods tested is broken down for clarity below:

1. Install range hood and set to desired speed (lowest or highest setting on range hood)
2. Heat ‘Top Surface’ to desired surface temperature (130°C, 160°C or 200°C ± 10°C)
3. Introduce CO2 tracer gas at 0.5% of range hood airflow rate
4. Wait until chamber undergoes 4 air changes
5. Take a minimum of 10 sets of measurements of three concentrations (C_exhaust, C_chamber, C_inlet), meaning that a set is made up of three measured values of the three different concentration values.
6. Plot the CE for each set of measurements and continue taking sets of measurements until the slope across the most recent 10 CE values has a magnitude less than 0.15 (i.e. less than 1.5% change in CE across all 10 measurements). See Appendix F for reference plot.
7. Take the last 10 of measurements and calculate an average value for each of the three concentrations, then use Equation 1 to calculate one final CE value, indicating that the CE test is complete.
8. Open door after the test is complete and clear out the test chamber until the difference between C_chamber and C_inlet is less than 50 ppm.

9. Keep range hood running at set speed and repeat steps 3 – 7 to calculate CE for *Test 2* while making sure that the surface is at the test temperature.
10. Dismount range hood
11. Re-install range hood and repeat steps 2 – 7 to calculate CE for *Test 3*.
12. Repeat steps 1 – 11 for all 6 range hoods analyzed in this study.
13. Change mounting height of range hood and repeat steps 1 – 12.

Test Scenarios

As noted previously, the six under the cabinet (UTC) range hoods tested had the same width and a design which is a style typical of residential wall-mounted range hoods. A representation of the UTC range hood profile and a photo of one of the range hoods tested is shown in Figure 38.

Figure 38: Typical UTC range hood analyzed in mounting height study

In total 108 different tests were performed on 36 unique test scenarios. Table 5 shows a breakdown of all the test scenarios performed in this study.

Table 5: Different test scenarios analyzed in mounting height study

Fan ID	Speed Setting	Airflow rate (cfm)	Heights (in.)
FAN 1	High	250	24, 27, 30
	Low	130	24, 27, 30
FAN 2	High	130	24, 27, 30

Table 6 (continued): Different test scenarios analyzed in mounting height study

	Low	110	24, 27, 30
FAN 3	High	310	24, 27, 30
	Low	120	24, 27, 30
FAN 4	High	340	24, 27, 30
	Low	160	24, 27, 30
FAN 5	High	350	24, 27, 30
	Low	160	24, 27, 30
FAN 6	High	300	24, 27, 30
	Low	160	24, 27, 30

Table 5 shows that each of the six fans (i.e. Fan 1 – 6) were tested at both height and low speeds over a wide range of flowrates (i.e. 110 – 350 cfm). Additionally, Table 1 shows that each combination of Fan and flowrate was tested at all three mounting heights of 24in., 27in. and 30in.

Results

As previously mentioned, there are multiple factors that can influence the capture efficiency (CE) and CE repeatability/reproducibility. Factors that can influence CE include, but are not limited to, the range hood type, airflow rate, mounting height and even test facility characteristics (e.g. inlet, tracer gas emitters, burner placement, etc.). The following four sub-sections presents the influence of mounting height on CE by testing six range hoods of similar design in accordance with ASTM-E3087.18 at three different mounting heights (24in., 27in. and 30in.) and at both the high speed (HS) and low speed (LS) settings. Additionally, each of the 6 range hoods was tested three times at HS and three times at LS, with two tests being performed back-to-back, and the third test being performed after a mandatory dismount/remount. It should be noted that the two tests performed back-to-back at each mounting height are to investigate the repeatability performance of CE at a specific height, whereas the mandatory dismount/remount is intended to provide insight on how mounting height influences the reproducibility of CE. The first sub-section presents the effects of mounting height on CE, as well as the uncertainty in CE (δ) where both of these metrics are determined based on guidelines presented in ASTM-E3087.18. The second sub-section presents the results for CE repeatability as a function of mounting height by analyzing the ΔCE metric, which is a measure of the variation between CE tests performed back-to-back, as well as the standard deviation (σ) between the 10-measurements, specified by the ASTM, that are averaged in order to determine CE. The third sub-section presents how the mounting height influences the CE reproducibility, which incorporates a mandatory dismount/remount of the rangehood and is indicated by the two reproducibility metrics of α and β. Finally, the influence of range hood mounting height on the overall variation between tests that are performed multiple times is investigated by analyzing the influence of the three mounting heights on the variability metric (ε).

Effects of mounting height on average CE and CE uncertainty

The influence of mounting height on capture efficiency (CE) was determined by observing how the CE, as well as the uncertainty in CE, varied at the different mounting heights, namely, 24in., 27in. and 30in. Each of the 6 range hoods was performed in accordance with ASTM-E3087.18 at the high speed (HS) and low speed (LS) for a total of 12 possible range hood configuration (i.e. range hood and speed setting). Additionally, each range hood configuration was performed three times. In total 108 tests were performed on 36 unique test scenarios (i.e. range hood, speed and mounting height). Figure 39 shows the average CE between the three tests performed at each test scenarios, with the error bars showing a range of +/-1 standard deviation.

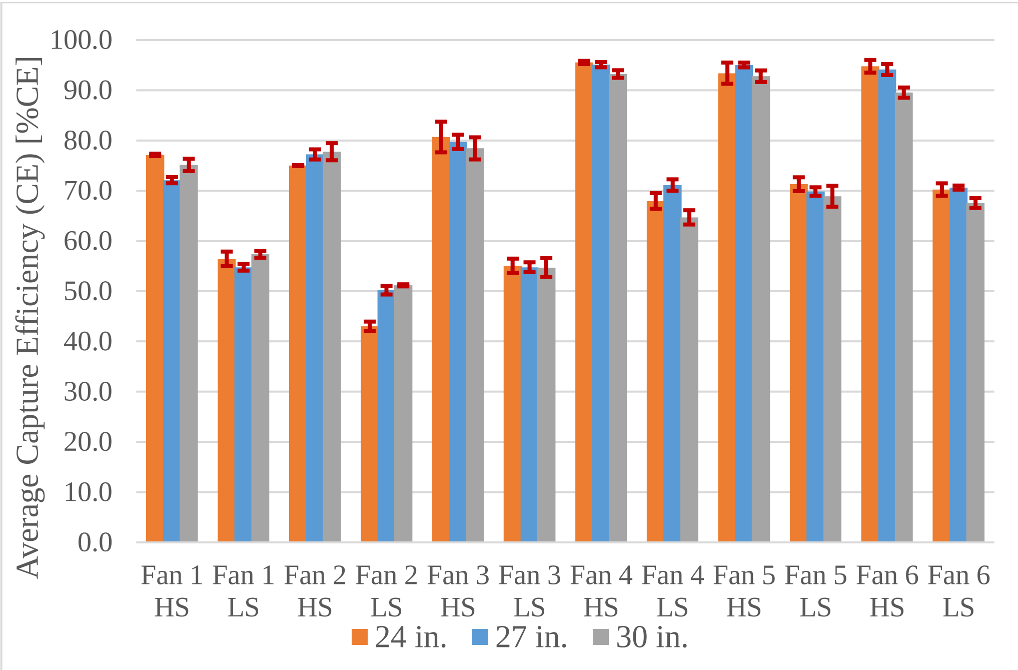


Figure 39: Average CE for 12 range hood configurations and 36 unique test scenarios analyzed in mounting height study. Error bars represent +/-1 standard deviation.

The results in Figure 39 show CE varying from 42.8%CE to 96.2%CE. Additionally, Figure 39 shows that seven out the 12 range hood configurations show a gradual increase/decrease in CE with increasing mounting height, with five showing a gradual decrease and two showing a gradual increase. Thus, indicating that the effects of mounting height on CE can vary between range hoods. The results in Figure 39 show that the 24in. mounting height has the highest CE 50% of the time and the 30in. mounting height has the lowest CE 67% of the, thus indicating the CE performance can be improved by lowering the mounting height. Additionally, the intermediate mounting height of 27in. provides a value for CE that is in between the other mounting heights 52% of the time.

Given that there are 12 range hood configurations (i.e. different configurations of range hoods and speed settings), and each configuration has three mounting heights, there are 36 possible test comparisons. Out of 36 possible test comparisons, 16 show a significant change in CE (δCE) (i.e. there is no overlap between +/- 1 standard deviation ranges shown in Figure 39). Table 6 shows the results of the 36 test comparisons analyzed in this section.

Table 7: Significant changes in CE (δCE) when changing height for 36 possible tests comparisons

	30 in. → 27 in.		30 in. → 24 in.		27 in. → 24 in.	
	Inc. or dec.	δCE	Inc. or dec.	δCE	Inc. or dec.	δCE
Fan 1 - HS	↓	**3.0**	↔	**2.0**	↑	**5.0**
Fan 1 - LS	↓	**2.6**	↔	**0.9**	↔	**1.7**
Fan 2 - HS	↔	**0.5**	↓	**2.8**	↓	**2.2**
Fan 2 - LS	↔	**1.0**	↓	**8.2**	↓	**7.2**
Fan 3 - HS	↔	**1.3**	↔	**2.3**	↔	**1.0**
Fan 3 - LS	↔	**0.1**	↔	**0.4**	↔	**0.3**
Fan 4 - HS	↔	**1.9**	↑	**2.3**	↔	**0.4**
Fan 4 - LS	↑	**6.4**	↑	**3.3**	↔	**3.2**
Fan 5 - HS	↑	**2.2**	↔	**0.6**	↔	**1.6**
Fan 5 - LS	↔	**0.9**	↑	**2.4**	↔	**1.5**
Fan 6 - HS	↑	**4.6**	↑	**5.2**	↔	**0.6**
Fan 6 - LS	↑	**3.1**	↑	**2.7**	↔	**0.4**

The results in Table 6 show that the maximum difference in CE when changing the mounting height for one range hood configuration is 8.2%CE and the minimum difference is 0.1%CE. When changing the mounting height from 27in. to 24in. only 25% of cases showed a significant change in CE (i.e. no overlap in the +/- 1 standard deviation range), compared with 50% of cases when changing the mounting height from 30in. to 27in., which indicates that changes in mounting height have less of an effect on CE at the lower mounting heights. The change in mounting height from 30in. to 24in. showed the most variation with 58% of cases showing a significant change in CE. When changing from 30in to 24in., the average change in CE is 2.7%CE, compared with an average δCE of 2.3%CE and 2.1%CE for 30in. to 27in. and 27in. to 24in., respectively.

In addition to analyzing the effects of mounting height on average CE and comparing the change in CE (δCE) at different mounting heights, the uncertainty in CE (δ) was also determined using the precision and bias procedure outlined in ASTM-E3087.18. Figure 40 shows the average δ values between the three CE tests for all 36 test scenarios.

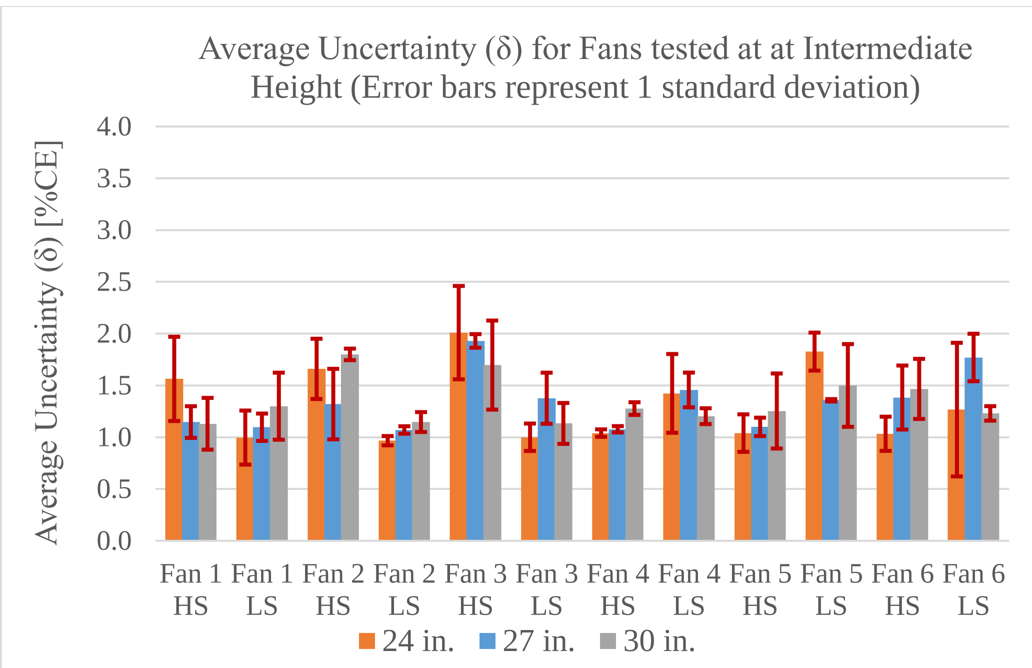


Figure 40: Average CE uncertainty (δ) for 12 range hood configurations and 36 unique test scenarios analyzed in mounting height study. Error bars represent +/-1 standard deviation.

The results in Figure 40 show that the average uncertainty is less than 2.0%CE for all but one test scenario. Specifically, Figure 40 shows that Fan 3 exhibits higher than usual uncertainty at HS, specifically at the lower mounting height of 24in. After closer inspection of Fan 3, it was determined that the higher uncertainty is likely a consequence of the range hood having vents on the top surface that are used to exhaust air during the re-circulation mode, but also create a large amount of leakage when the range hood is operating in exhaust mode. Since the average uncertainty was typically less than 2.0%CE and the maximum change in CE (δCE) was 8.2%CE (i.e. greater than +/-2.0%CE), it can be concluded that mounting heights have a significant effect on CE.

In general, out of 36 possible comparisons only four showed a significant difference in uncertainty (i.e. no overlap in the +/- 1 standard deviation range). Furthermore, the maximum significant difference in average δ was determined to be 0.5%CE, which occurred for Fan 6 at LS. It should be noted that three out of the four significant difference in average δ occurred at the low speed, thus indicating that the effects of mounting height on uncertainty are more prevalent at lower speeds. Additionally, Table 7 shows the results for uncertainty ranked from highest to lowest for the 12 range hood configurations. It should be noted that a rank of 1st indicates the mounting height with the highest uncertainty, 2nd indicates the second highest uncertainty and so forth.

Table 8: Uncertainty in CE (δ) ranked from highest (1st) to lowest (3rd) for cases analyzed in mounting height study

Uncertainty (δ) [%CE]	24 in.		27 in.		30 in.	
	Rank	Value	Rank	Value	Rank	Value
Fan 1 - HS	**1st**	**1.6**	**2nd**	**1.2**	**3rd**	**1.1**

Table 9 (continued): Uncertainty in CE (δ) ranked from highest (1st) to lowest (3rd) for cases analyzed in mounting height study

Fan 1 - LS	**3rd**	**1.0**	**2nd**	**1.1**	**1st**	**1.3**
Fan 2 - HS	**2nd**	**1.7**	**3rd**	**1.3**	**1st**	**1.8**
Fan 2 - LS	**3rd**	**1.0**	**2nd**	**1.1**	**1st**	**1.2**
Fan 3 - HS	**1st**	**2.0**	**2nd**	**1.9**	**3rd**	**1.7**
Fan 3 - LS	**3rd**	**1.0**	**1st**	**1.4**	**2nd**	**1.1**
Fan 4 - HS	**3rd**	**1.0**	**2nd**	**1.1**	**1st**	**1.3**
Fan 4 - LS	**2nd**	**1.4**	**1st**	**1.5**	**3rd**	**1.2**
Fan 5 - HS	**3rd**	**1.0**	**2nd**	**1.1**	**1st**	**1.3**
Fan 5 - LS	**1st**	**1.8**	**3rd**	**1.4**	**2nd**	**1.5**
Fan 6 - HS	**3rd**	**1.0**	**2nd**	**1.4**	**1st**	**1.5**
Fan 6 - LS	**2nd**	**1.3**	**1st**	**1.8**	**3rd**	**1.2**

The results in Table 7 show that the 30in. mounting height has the highest uncertainty 50% of the time, whereas the 24in. mounting height has the lowest uncertainty 50% of the time. Thus, it can be concluded that a lower mounting height (i.e. 24in.) will typically give lower uncertainty results. It should also be noted that the 27in. mounting height has an uncertainty that is in between the two other heights 58% of the time, indicating that an intermediate mounting height typically provides an uncertainty approximation within the overall range

Effects of mounting height on the repeatability of capture efficiency (CE)

The influence of mounting height on the repeatability of capture efficiency (CE) was determined by analyzing two different metrics; namely, the repeatability metric (ΔCE), which represents the absolute difference between tests performed back-to-back, and the standard deviation (σ) between the 10 CE measurements averaged to determine CE. It is important to note that ASTM-E3087.18 specifies a minimum of 10 measurements to be taken after four air change and then averaged to determine CE. However, additional measures, which were described in a previous section, were taken to ensure a steady state CE across the 10 CE measurements; namely a slope of 0.15%CE, or less, across the 10 measurements. Figure 41 shows the ΔCE repeatability metric for the 12 range hood configurations.

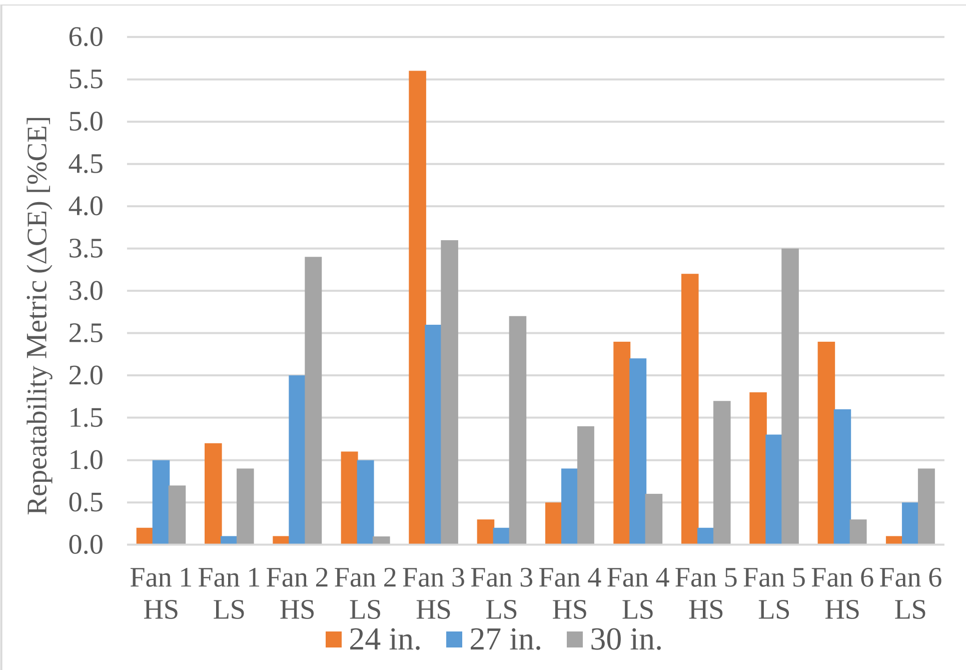


Figure 41: Repeatability metric (ΔCE) for 12 range hood configurations and 36 unique test scenarios analyzed in mounting height study.

Figure 41 shows that five out of 12 cases show a difference in ΔCE greater than 2.0%CE (i.e. the typical uncertainty experienced in this study) when comparing mounting heights, which implies that the mounting height can have a significant effect on the CE repeatability. It should be noted that all range hood configurations except one, namely Fan 3 at HS, have a value for ΔCE less than or equal to 3.5%CE. Excluding Fan 3 completely, which is the fan with re-circulating vents on the top surface, only three cases, which are extreme high/low mounting heights have a ΔCE greater than 2.5%CE (i.e. the maximum uncertainty experienced in this study). Otherwise, all tests performed at 27in. had a ΔCE less than 2.5%CE.

The values for ΔCE were ranked from highest to lowest with 1st indicating the highest ΔCE value for a specific range hood configuration and 3rd indicating the lowest ΔCE value for a range hood configuration. Table 8 shows the rankings of the ΔCE metric for all 12 range hood configurations.

Table 10: ΔCE metric ranked from highest to lowest for all 12 range hood configurations tested in mounting height study

ΔCE [%CE]	24 in.		27 in.		30 in.	
	Rank	Value	Rank	Value	Rank	Value
Fan 1 - HS	**3rd**	**0.2**	**1st**	**1.0**	**2nd**	**0.7**
Fan 1 - LS	**1st**	**1.2**	**3rd**	**0.1**	**2nd**	**0.9**
Fan 2 - HS	**3rd**	**0.1**	**2nd**	**2.0**	**1st**	**3.4**
Fan 2 - LS	**1st**	**1.1**	**2nd**	**1.0**	**3rd**	**0.1**
Fan 3 - HS	**1st**	**5.6**	**3rd**	**2.6**	**2nd**	**3.6**
Fan 3 - LS	**2nd**	**0.3**	**3rd**	**0.2**	**1st**	**2.7**
Fan 4 - HS	**3rd**	**0.5**	**2nd**	**0.9**	**1st**	**1.4**
Fan 4 - LS	**1st**	**2.4**	**2nd**	**2.2**	**3rd**	**0.6**
Fan 5 - HS	**1st**	**3.2**	**3rd**	**0.2**	**2nd**	**1.7**
Fan 5 - LS	**2nd**	**1.8**	**3rd**	**1.3**	**1st**	**3.5**
Fan 6 - HS	**1st**	**2.4**	**2nd**	**1.6**	**3rd**	**0.3**
Fan 6 - LS	**3rd**	**0.1**	**2nd**	**0.5**	**1st**	**0.9**

The data presented in Table 8 shows the values for ΔCE ranging from 0.1%CE to 5.6%CE for all the range hood configuration analyzed. The results in Table 8 show that the 30in. case has the highest ΔCE 42% of the time (i.e. poorest repeatability) and the 24in. case has the highest ΔCE 50% of the time. The 27in. mounting height has the lowest ΔCE 42% of the time (i.e. best repeatability performance). Furthermore, the 27in. mounting height has a value for ΔCE that is in between the other two mounting heights

58% of the time and has the highest ΔCE only once. These results would seem to indicate that the repeatability performance can be improved at an intermediate mounting high as opposed to extreme high/low mounting heights.

As another means to quantify the repeatability of CE, the standard deviation (σ) between the 10 CE measurements used to determine CE was recorded for each of the three tests, with the average σ value for each range hood configuration shown in Figure 42**.**

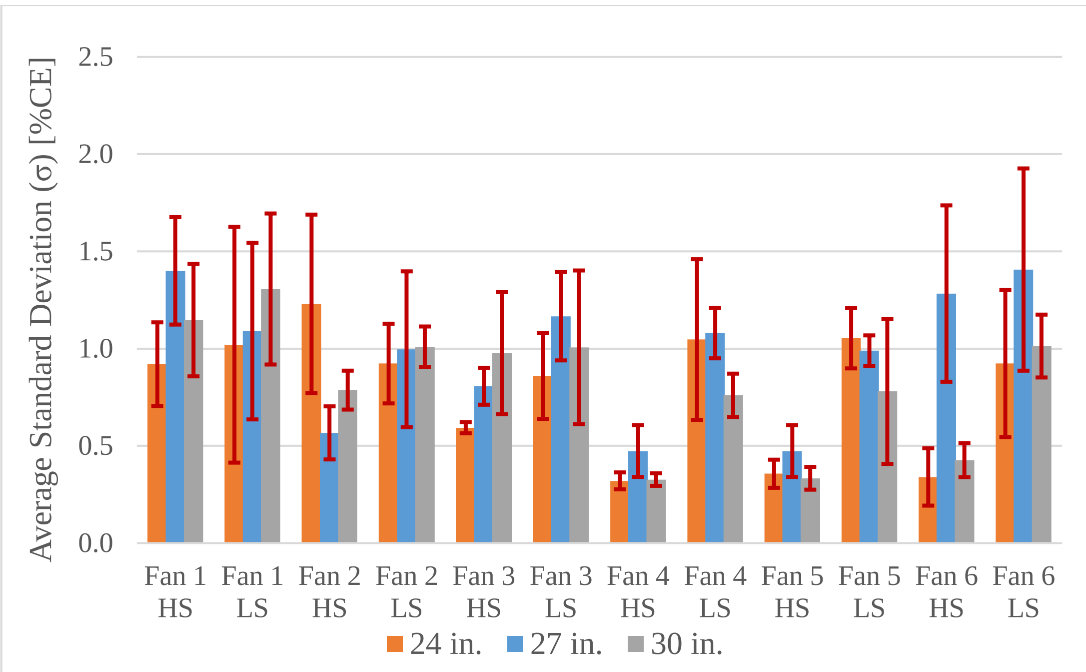


Figure 42: Standard deviation (σ) for 12 range hood configurations and 36 unique test scenarios analyzed in mounting height study. Error bars represent +/-1 standard deviation.

Figure 42 shows that six out of 36 possible comparisons show a significant difference in σ (i.e. no overlap in the +/- 1 standard deviation range). However, the maximum difference in σ when comparing mounting heights for a specific range hood configuration is 1.0%CE, which is within the typical uncertainty (δ) experienced in this study. Additionally, all average σ values are less than 1.5%CE and all σ values are less than 2.0%CE, indicating that the repeatability of CE is not heavily influenced by mounting height when quantified using σ.

Effects on CE Reproducibility

Similar to the analysis performed on capture efficiency (CE) repeatability, the effects of mounting height on CE reproducibility were determined using two reproducibility metrics, α and β. The reproducibility is different from the repeatability in that the reproducibility requires a mandatory dismount and then remount of the rangehood. In contrast, the repeatability only accounts for the changes in CE tests performed back-to-back with no change in the test configuration (i.e. burner spacing within ASTM prescribed tolerances, flexible duct segment connecting to chamber exhaust duct, etc.). To reiterate, each range hood was tested two times at the high speed (HS) and then two times at the low speed (LS) before being dismounted and remounted for one final HS and LS test. Figure 43 shows the effects of range hood mounting height on the CE reproducibility metric α.

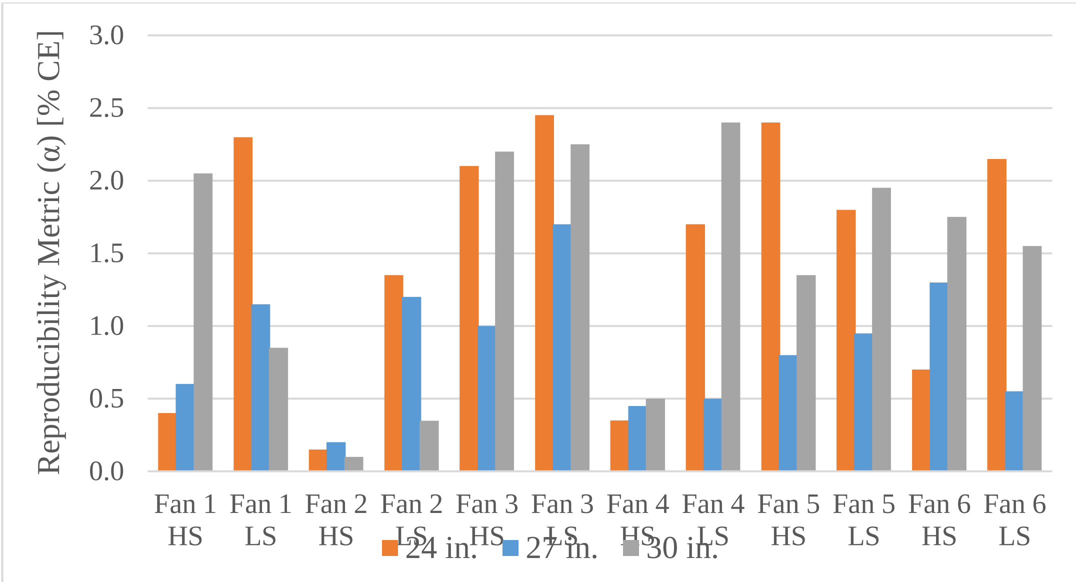


Figure 43: Reproducibility metric (α) for 12 range hood configurations and 36 unique test scenarios analyzed in mounting height study.

The results in Figure 43 show the same trend to repeatability (ΔCE) where six out of 12 cases show that an intermediate mounting height can improve reproducibility as opposed to the extreme high/low heights. Additionally, all values for α are less than 2.5%CE, including Fan 3 which previously showed a ΔCE value greater than 5.5%CE. Thus, it can be concluded that although a range hood may exhibit poor repeatability performance, increased testing (i.e. dismounting/remounting and testing a third time) can yield a more accurate representation of the true CE value. Table 9 shows the rankings of the α metric by height for all 12 range hood configurations, with 1st indicating the worst reproducibility performance and 3rd indicating the best reproducibility performance.

Table 11: α metric ranked from highest to lowest for all 12 range hood configurations analyzed in mounting height study

α [%CE]	24 in.		27 in.		30 in.	
	Rank	Value	Rank	Value	Rank	Value
Fan 1 - HS	**3rd**	**0.4**	**2nd**	**0.6**	**1st**	**2.1**
Fan 1 - LS	**1st**	**2.3**	**2nd**	**1.2**	**3rd**	**0.9**

Table 12 (continued): α metric ranked from highest to lowest for all 12 range hood configurations analyzed in mounting height study

Fan 2 - HS	**2nd**	**0.1**	**1st**	**0.2**	**3rd**	**0.1**
Fan 2 - LS	**1st**	**1.4**	**2nd**	**1.2**	**3rd**	**0.3**
Fan 3 - HS	**1st**	**2.1**	**3rd**	**1.0**	**2nd**	**2.2**
Fan 3 - LS	**1st**	**2.5**	**3rd**	**1.7**	**2nd**	**2.3**
Fan 4 - HS	**3rd**	**0.4**	**2nd**	**0.5**	**1st**	**0.5**
Fan 4 - LS	**2nd**	**1.7**	**3rd**	**0.5**	**1st**	**2.4**
Fan 5 - HS	**1st**	**2.4**	**3rd**	**0.8**	**2nd**	**1.3**
Fan 5 - LS	**2nd**	**1.8**	**3rd**	**1.0**	**1st**	**2.0**
Fan 6 - HS	**3rd**	**0.7**	**2nd**	**1.3**	**1st**	**1.8**
Fan 6 - LS	**1st**	**2.2**	**3rd**	**0.5**	**2nd**	**1.6**

Similar to the results for ΔCE, the data presented in Table 9 once again shows that the reproducibility (α) performance is the worst at the extreme high and low mounting heights in all cases except one. Specifically, the 24in. case has the highest α (i.e. poorest reproducibility) 50% of the time and the 30in. case has the highest α 42% of the time. Furthermore, the 27in. cases has the lowest value for α (i.e. best reproducibility performance) 50%. It should be noted that maximum value for α is 2.5%CE, which is Fan 3 – LS, and the minimum value is 0.1%CE. Additionally, the maximum deviation in α when varying the mounting height is 1.9%CE, which is just within the typical uncertainties experienced in this study. Thus, it can be concluded that the mounting height only has a minor effect, if any at all, on the reproducibility metric α.

As another measure of reproducibility, the results for the β metric are shown in Figure 44**,** which is the maximum difference between the final CE test after the mandatory dismount/remount and the initial CE test performed back-to-back**.**

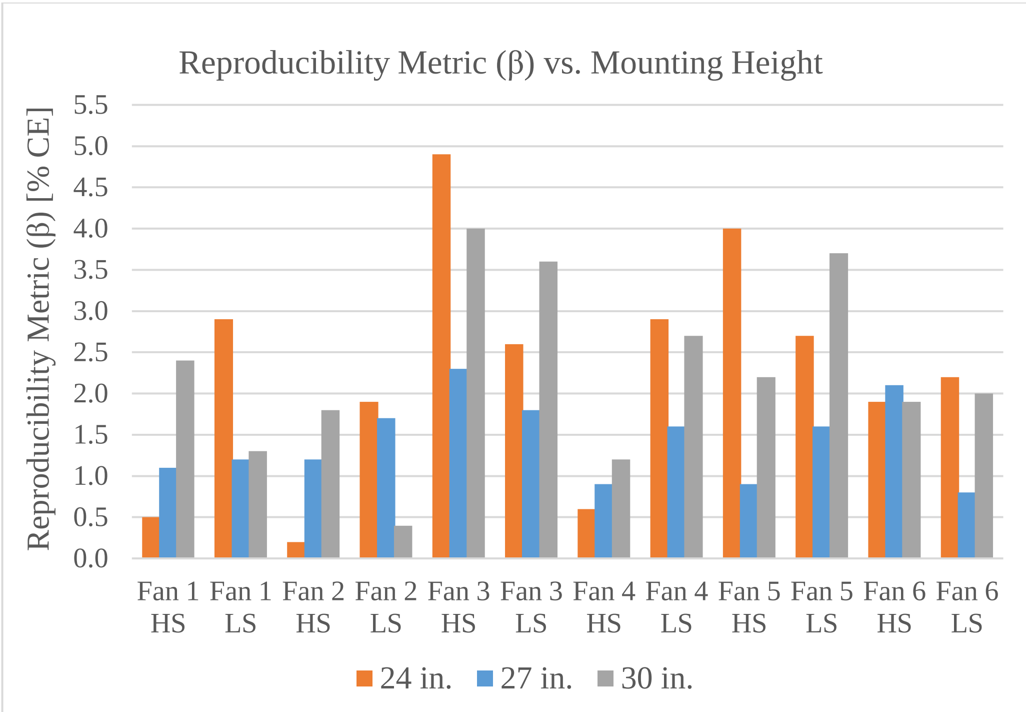


Figure 44: Reproducibility metric (β) for 12 range hood configurations and 36 unique test scenarios analyzed in mounting height study.

The results in Figure 44 show that the reproducibility metric is β minimized at the 27in. mounting height for seven out of 12 range hood configurations. Additionally, the maximum deviation in β between mounting heights is 3.1%CE, which occurs for Fan 5 HS, and is outside the range of typical uncertainty experienced in this study. Thus, it can once again be concluded that mounting height has a minimal effect on reproducibility and the β metric can be improved at an intermediate mounting height as opposed to an extreme high/low mounting height.

The results for the β metric were sorted from highest to lowest for the three mounting heights of each range hood configuration, with the results being shown in Table 10. It is important to note that the 1st, or highest, β metric indicates the worst reproducibility performance, 2nd indicates the second worst reproducibility performance and so forth.

Table 13: β metric ranked from highest to lowest for all 12 range hood configurations analyzed in mounting height study

β [%CE]	24 in.		27 in.		30 in.	
	Rank	Value	Rank	Value	Rank	Value
Fan 1 - HS	**3rd**	**0.5**	**2nd**	**1.1**	**1st**	**2.4**
Fan 1 - LS	**1st**	**2.9**	**3rd**	**1.2**	**2nd**	**1.3**
Fan 2 - HS	**3rd**	**0.2**	**2nd**	**1.2**	**1st**	**1.8**
Fan 2 - LS	**1st**	**1.9**	**2nd**	**1.7**	**3rd**	**0.4**
Fan 3 - HS	**1st**	**4.9**	**3rd**	**2.3**	**2nd**	**4.0**
Fan 3 - LS	**2nd**	**2.6**	**3rd**	**1.8**	**1st**	**3.6**
Fan 4 - HS	**3rd**	**0.6**	**2nd**	**0.9**	**1st**	**1.2**
Fan 4 - LS	**1st**	**2.9**	**3rd**	**1.6**	**2nd**	**2.7**
Fan 5 - HS	**1st**	**4.0**	**3rd**	**0.9**	**2nd**	**2.2**
Fan 5 - LS	**2nd**	**2.7**	**3rd**	**1.6**	**1st**	**3.7**
Fan 6 - HS	**2nd**	**1.9**	**1st**	**2.1**	**2nd**	**1.9**
Fan 6 - LS	**1st**	**2.2**	**3rd**	**0.8**	**2nd**	**2.0**

The results in Table 10 show that 24in. has the worst reproducibility performance 50% of the time and 30in. has the worst reproducibility 42% of the time. Furthermore, the 27in. mounting height, which represents the midrange, only has the highest β in one instance, which is a value of 2.1%CE for Fan 2 LS. The maximum value of β is 4.9%CE and the minimum value is 0.2%CE, which is wider than the range for α of 0.2%CE to 2.5%CE. Thus, it can be concluded that the β metric may be advantageous in future ASHRAE/HVI certifications as it provides a wider range for the expected variation for tests performed at different instances (i.e. incorporation of a dismount/remount). Additionally, similar to α, the β metric has a smaller range than ΔCE, with a range of values of 0 – 4.9%CE for β compared with a range of 0 – 5.6%CE for ΔCE. Therefore, it can be concluded that increased testing can provide a more accurate representation for CE (e.g. a narrower range of CE values).

Effects on CE Variability

The influence of mounting height on capture efficiency (CE) variability was determined by analyzing the coefficient of variation (ε) between the three CE tests performed at each of the three mounting heights – 24in., 27in. and 30in. The results for the ε value at the three mounting heights of the 12 range hood configurations is shown in Figure 45**.**

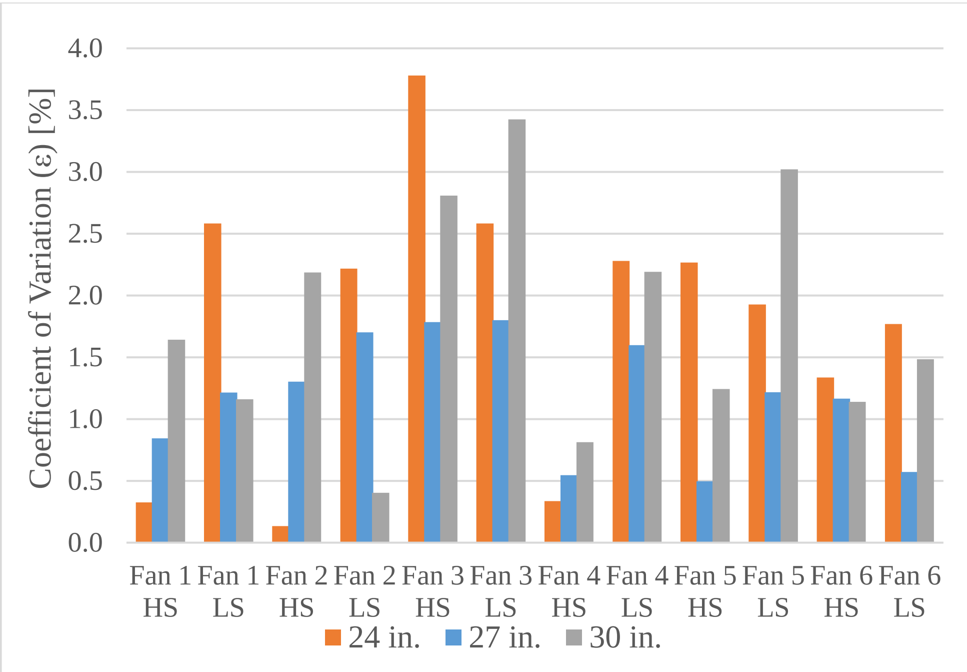


Figure 45: Coefficient of variation (ε) for 12 range hood configurations analyzed in mounting height study

The results in Figure 45 show that for six out of 12 cases ε is minimized at 27in. All values of ε were less than 4.0% and excluding Fan 3, which is the fan with re-circulating vents on top, all values of ε are less than or equal to 3.0%. The maximum deviation in ε when varying mounting height is 2.0%, which is the difference between an ε value of 3.8% and an ε value of 1.8%. Additionally, the ε value were sorted from highest to lowest across the different mounting heights of each test configuration, where 1st indicates the mounting height with the highest ε value and 3rd indicates the mounting height with lowest ε value**.** Table 11 shows the results for the ε values tabulated from highest to lowest depending on the mounting height.

Table 14: Coefficient of variation (ε) tabulated from highest to lowest for 12 range hood configurations analyzed in mounting height study

COV [%]	24 in.		27 in.		30 in.	
	Rank	Value	Rank	Value	Rank	Value
Fan 1 - HS	**3rd**	**0.3**	**2nd**	**0.8**	**1st**	**1.6**
Fan 1 - LS	**1st**	**2.6**	**2nd**	**1.2**	**3rd**	**1.2**
Fan 2 - HS	**3rd**	**0.1**	**2nd**	**1.3**	**1st**	**2.2**
Fan 2 - LS	**1st**	**2.2**	**2nd**	**1.7**	**3rd**	**0.4**
Fan 3 - HS	**1st**	**3.8**	**3rd**	**1.8**	**2nd**	**2.8**
Fan 3 - LS	**2nd**	**2.6**	**3rd**	**1.8**	**1st**	**3.4**
Fan 4 - HS	**3rd**	**0.3**	**2nd**	**0.5**	**1st**	**0.8**
Fan 4 - LS	**1st**	**2.3**	**3rd**	**1.6**	**2nd**	**2.2**
Fan 5 - HS	**1st**	**2.3**	**3rd**	**0.5**	**2nd**	**1.2**
Fan 5 - LS	**2nd**	**1.9**	**3rd**	**1.2**	**1st**	**3.0**
Fan 6 - HS	**1st**	**1.3**	**2nd**	**1.2**	**3rd**	**1.1**
Fan 6 - LS	**1st**	**1.8**	**3rd**	**0.6**	**2nd**	**1.5**

The results in Table 11 show the 24in. mounting height has the highest variability (ε) for seven out of 12 range hood configurations. Thus, it should be noted, that although a low mounting height may reduce uncertainty of a specific test, one also runs the risk of increasing the variability across multiple tests. Furthermore, the 27in. mounting height never exhibits the highest ε value and has the lowest ε value for more than any of the other heights. Additionally, ε has a value that is in between the other two mounting heights 50% of the time. Therefore, it can be concluded that the coefficient of variation is not only minimized at 27in. mounting height but typically gives a representation for ε that is in between the other extreme high/low mounting heights.

Summary

Previous studies have shown that the mounting height of a range hood can affect the perceived CE performance. However, in all these studies the variations in height are only limited to two different heights, and the test procedures used did not strictly adhere to the guidelines for CE testing described in ASTM-E3087.18. Furthermore, none of these studies emphasized studying the effects of mounting height on CE repeatability, uncertainty or variability, but rather the use of multiple heights in past studies was primarily to increases the number of unique CE test scenarios. The objective of this study is to identify, quantify and evaluate how changing the range hood mounting height effects measured values of CE, as well as the repeatability/reproducibility of CE. Additionally, this study also investigates whether there is an optimum mounting height at which variations between repeat CE tests are minimized.

In the study reported herein, CE testing was performed on 6 traditional under the cabinet (UTC) range hoods of equivalent widths and at three different mounting heights – 24in., 27in. and 30 in. Each range hood was tested three times at both the high speed (HS) and low speed (LS) for the various mounting heights. Specifically, each range hood was tested two times back-to-back without altering the test set-up and then dismounted/remounted before being tested a third time. It should be noted that the test cycle, which incorporates a mandatory dismount/re-mount, is to observe how mounting height influences not only CE, but also its repeatability and reproducibility. In total, 108 CE tests were performed on 36 unique test scenarios (i.e. combination of range hood, mounting height and speed setting).

Results showed that CE varied from 42.8%CE to 96.2%CE with seven out of 12 range hoods showing a gradual increase/decrease in mounting height. Additionally, results showed that that the 24in. mounting height had the highest CE 50% of the time and the 30in. mounting height has the lowest CE 67% of the, thus indicating that CE performance can be improved by lowering the mounting height. Out of 36 possible test comparisons, 16 showed a significantly different change in CE (δCE) when changing the mounting height, with a maximum difference of 8.2%CE when changing the mounting height of a specific range hood configuration (i.e. range hood and speed setting). When changing the mounting height from 27in. to 24in. only 25% of cases showed a significant change in CE, compared with 50% of cases when changing the mounting height from 30in. to 27in. and 58% of cases when changing from 30in. to 24in. Thus, indicating that mounting height effects are less dominant at lower mounting heights. The average uncertainty in CE was less than 2.0%CE for all but one case, which was Fan 3 HS at 24in. Closer inspection of Fan 3 showed that the higher uncertainty is likely a consequence of Fan 3 having vents on the top surface that are used to exhaust air during re-circulation mode, but also create a large amount of leakage when the range hood is operating in exhaust mode. Therefore, it is possible that future ASHRAE/HVI certification standards be written such that re-circulating vents are sealed off during testing. Results showed that the 30in. mounting height had the highest uncertainty 50% of the time, whereas the 24in. mounting height has the lowest uncertainty 50% of the time. Thus, it can be concluded that a lower mounting height (i.e. 24in.) will typically give lower uncertainty results. It should also be noted that the 27in. mounting height has an uncertainty that is in between the two other heights 58% of the time indicating that an intermediate mounting height typically provides an uncertainty within the typical range of uncertainty within the typical uncertainty range for a specific range hood.

In analyzing the repeatability metric (ΔCE), which represents the absolute difference between tests performed back-to-back, five out 12 cases showed a difference in ΔCE greater than 2.0%CE (i.e. the typical uncertainty experienced in this study) when changing mounting height, thus indicating that mounting height can have a significant effect on repeatability. Additionally, 42% showed ΔCE to be minimized at 27in. (i.e. best repeatability performance), as opposed to 50% of the 24in. cases and 42% of the 30in. cases having the highest ΔCE value (i.e. worst repeatability performance). Therefore, it was concluded that the CE repeatability performance can be optimized at an intermediate mounting height, as opposed to an extreme high/low mounting height.

Analysis of the standard deviation (σ) between the 10 measurements that are used to calculate CE, showed that all σ values were less than 2.0%CE. Six out of 12 range hood configurations showed a significant difference in σ when changing the mounting height; however, the maximum difference in σ when varying mounting heights is 1.0%CE, which is within the typical uncertainty (δ) experienced in this study. Therefore, it was concluded that the mounting height has very little effect on the standard deviation.

Analysis of the reproducibility metric α, which incorporates a mandatory dismount/remount, showed α is minimized at the intermediate 27in. mounting height for 50% of cases. Additionally, all values for α are less than 2.5%CE, including Fan 3 which previously showed a ΔCE value greater than 5.5%CE. Thus, it was concluded that although a range hood may exhibit poor repeatability performance, increased testing (i.e. dismounting/remounting and testing a third time) can yield a more accurate representation of the true CE value. The maximum deviation in α when varying the mounting height is 1.9%CE, which is within the typical uncertainties experienced in this study; therefore, the mounting height was concluded to have a minor effect on the reproducibility metric α, unlike the repeatability metric ΔCE. The range of 0.1%CE to 5.6%CE for ΔCE being wider than the range of 0.2 – 2.5%CE for α suggests that dismounting/remounting the test unit can reduce the range of variation between CE tests and thus provide a more accurate measurement for CE.

The results for the reproducibility metric β showed the 27in. mounting height, which represents the midrange, only has the highest β in one instance, which is a value of 2.1%CE for Fan 6 HS. The maximum value of β is 4.9%CE and the minimum value is 0.2%CE, which is wider than the range for α of 0.1 – 2.5%CE. Thus, it can be concluded that the β metric may be advantageous in future ASHRAE/HVI certifications as it provides a wider range for the expected variation for tests performed at different instances (i.e. incorporation of a dismount/remount). Additionally, the β metric has a smaller range than ΔCE, with a range of values of 0.2 – 4.9%CE for β compared with a range of 0.1 – 5.6%CE for ΔCE. Therefore, it can be concluded that increased testing, and specifically dismounting/remounting, can provide a narrower range for the true CE value.

All values of ε were less than 4.0% and excluding Fan 3, which is the fan with re-circulating vents on top, all values of ε are less than or equal to 3.0%. Results showed that the 24in. mounting height has the highest variability (ε) for seven out of 12 range hood configurations. Therefore, although testing at lower mounting heights may reduce the uncertainty for a specific test, this comes at the cost of increasing the variability across multiple test. Furthermore, the 27in. mounting height exhibits the highest ε for only one out of 12 cases and has the lowest value for ε more than any of the other heights. Additionally, ε has a value that is in between the other two mounting heights 50% of the time. Therefore, it can be concluded that the coefficient of variation is not only minimized at 27in. mounting height but typically gives a representation for ε that is in between the other extreme high/low mounting heights.

Therefore, it can be concluded that mounting height has a significant effect on CE performance with a maximum deviation in CE of 8.2%CE when changing heights. CE improves (i.e. higher CE value) by lowering the mounting height, as well as CE uncertainty being reduced, however, lower mounting heights were found to create increased variability between tests. In general, when analyzing the repeatability, reproducibility and variability of CE, it was found that the 27in. mounting height hardly gave the poorest results for any these performance metrics. In fact, the 27in. gave a value that was in between the extreme high/low mounting heights more times than others. Therefore, it is possible that future certification testing incorporate an intermediate 27in. mounting height as opposed to an extreme high/low height. Recirculation vents on the top surface of one fan caused increased uncertainty/variability and reduced repeatability/reproducibility performance, therefore it is recommended that future ASHRAE/HVI certification standards be written such that re-circulating vents are sealed off during testing. Furthermore, the range of 0.1 – 5.6%CE for ΔCE being wider than the range of 0 – 2.5 for α, suggests that increased testing, and specifically dismounting/remounting of the range hood, can reduce the range of variation between CE tests and thus provide a more accurate measurement for CE. Furthermore, the wider range of 0.2 – 4.9%CE for β compared to 0.2 – 2.5% for α suggests that the β metric may be advantageous in future ASHRAE/HVI certifications as it provides a wider range for the expected variation for tests performed at different instances (i.e. incorporation of a dismount/remount).

CHAPTER VII

THE EFFECTS OF RANGE HOOD DISCHARGE ORIENTATION ON CAPTURE EFFICIENCY

Overview

Previous studies on range hood capture efficiency only utilize one specific discharge orientation for the range hoods tested, namely a vertical discharge orientation. Even though range hoods can be installed with horizontal discharge orientations, there are no studies available in open literature that show a range hood utilizing a horizontal discharge orientation, much less being tested in accordance with the newly developed capture efficiency (CE) standard, ASTM-E3087.18. Therefore, it is important to investigate the effects of range hood discharge orientation on CE as well as CE repeatability, reproducibility and variability. In the study reported herein, the CE test facility presented and discussed in this dissertation was modified to accommodate range hoods with horizontal discharge.

In the study reported herein, CE testing was performed on five traditional under the cabinet (UTC) range hoods with equivalent widths of 30in. Each range hood was tested at both the high speed (HS) and low speed (LS) for a total of 10 range hood configurations (i.e. unique combinations of range hood and speed). Additionally, each range hood configuration was tested using horizontal and vertical discharges, for a total of 20 unique test scenarios (i.e. unique combination of range hood, speed and discharge orientation). Finally, three CE tests were performed at each unique test scenario for a total of 60 tests. Specifically, each range hood was tested three times; two times back-to-back without altering the test set-up and then dismounted/remounted before being tested one final time. It should be noted that the mandatory dismount/re-mount during the test cycle is to observe how mounting height influences not only CE, but also its repeatability and reproducibility.

Additionally, since it was observed in the previous chapter that some range hood geometry features (i.e. re-circulation vents on top of hood) can cause increased variations between tests, additional measures were taken to ensure all openings on the range hood (i.e. re-circulation vents and holes for mounting) were sealed prior to testing. In this study, the additional measures taken to seal the openings on the range hood were done in order to eliminate one of the various factors causing variation between tests. Therefore, by eliminating one factor leading to variations between tests, the results of this study highlight how the discharge orientation influences CE, as well as CE repeatability/reproducibility.

Problem Statement

The objective of this study is to identify, quantify and evaluate how changing the range hood discharge orientation (i.e. horizontal vs. vertical) affects measured values of capture efficiency (CE). An additional question that needs addressing is whether the CE test method developed by the American Society of Testing and Materials (ASTM) is valid for range hoods oriented with horizontal discharge, as all previous studies available in the open literature utilized a vertical discharge only. Furthermore, in line with studying the effects of range hood discharge orientation on CE, this study also investigates the effect of discharge orientation on CE repeatability and reproducibility (i.e. variations in calculated CE values for repeated tests) and whether or not there is an optimum discharge orientation at which variations between repeat CE tests are minimized.

Experimental Methods

Test Facility

Much like all the experimental studies performed in this dissertation, including this chapter, range hood testing was performed by using the aforementioned test chamber that was designed and built at the RELLIS Energy Efficiency Laboratory (REEL) at Texas A&M University. The test chamber has dimensions of 4m x 5m (13.1ft x 16.5ft) with a ceiling height of 3m (10ft). The chamber has a leakage rate of 1.7ACH corresponding to chamber conditions of 50Pa, which is less than the 2.5ACH specified by the ASTM. The exhaust duct was built in accordance with ASTM-E3087.18 and has a leakage rate of 1.3L/s (2.7cfm) at 25Pa gage pressure, which is less than the ASTM specified value of 2.5L/s at 25Pa.

Airflow through the exhaust duct is measured by using a venturi tube that was built in accordance with the International Standard Organization (ISO) Standard ISO5167-4: Measurement of Fluid Flow by Means of a Pressure Differential Device. The venturi tube measurement system has an uncertainty of 3.5% of the measured airflow, which is less than the ASTM-E3087.18 required value of 5% or 2.5L/s (whichever is greater). The setup for the horizontal discharge tests, utilized the same venturi tube (i.e. minimizes cost and variability between measurements). Therefore, in order to accommodate the horizontal discharge of the range hood while still ensuring the same venturi tube is used, a separate exhaust duct was installed, and a y-fitting was used to connect to the horizontal discharge duct to the venturi tube. The chamber modifications described are shown in Figure 46 below.

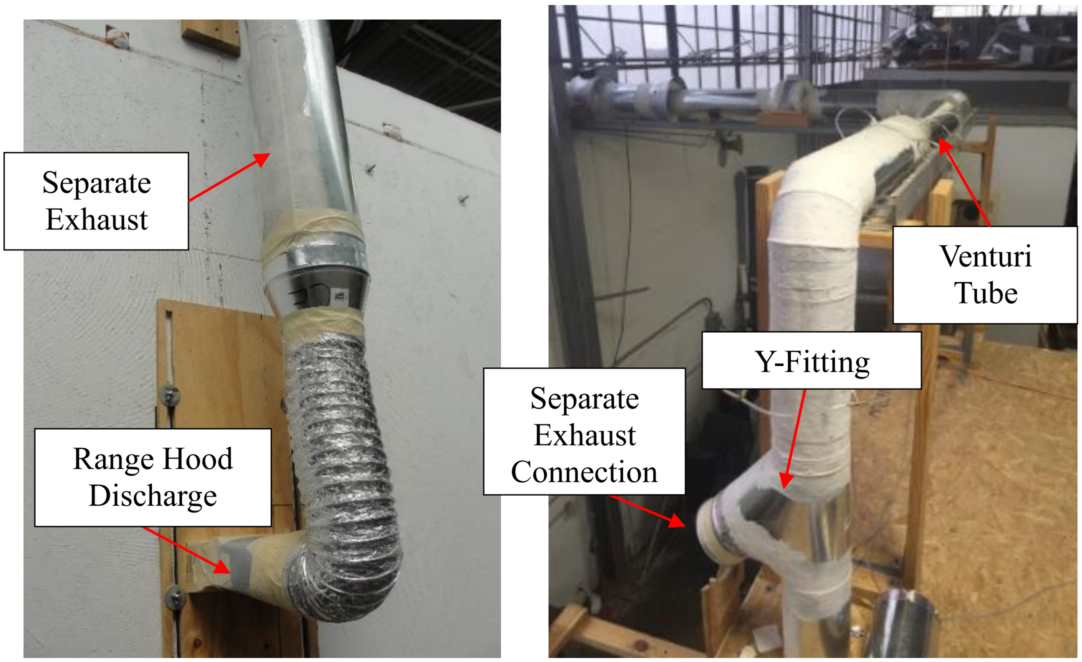


Figure 46: Chamber modifications performed to accommodate horizontal discharge

Test Procedure

The uniform test procedure presented earlier was used in this evaluation of the effects of range hood discharge orientation on CE. The test sequence followed involved first testing each range hood two times consecutively using vertical discharge (CE 1V and CE 2V) in order to observe the effects of discharge orientation on CE repeatability (i.e. difference between tests run consecutively). Next, the range hood was dismounted, and all other range hoods were tested twice in vertical orientation before the chamber discharge orientation was changed from vertical to horizontal. Next, two horizontal orientation CE tests (CE 1H and CE 2H) were performed to compare the effects of horizontal discharge orientation on CE repeatability (i.e. tests run consecutively with no changes to test set-up). After each range hood was tested twice in the horizontal orientation, the test chamber orientation was changed back to vertical for one final CE test (CE 3V) on all five range hoods analyzed in this study. Finally, the test chamber orientation was changed once again to horizontal and each range hood was tested a final time in horizontal orientation (CE 3H) to observe the effects of discharge orientation on CE reproducibility. Table 12 breaks down the test procedure described above for clarity.

Table 15: Test procedure followed to acquire CE 1V - CE3V and CE 1H - CE 3H for all fans investigated in discharge orientation study

Step	Description	Product
1	Test Fan 1 two times back-to-back with vertical discharge orientation	CE 1V and CE 2V for Fan 1
2	Dismount Fan 1 and repeat Step 1 for Fan 2 – Fan 5	CE 1V and CE 2V for Fan 2 – Fan 5
3	Switch to horizontal orientation and test Fan 1 two times back-to-back	CE 1H and CE 2H for Fan 1
4	Dismount Fan 1 and repeat Step 3 for Fan 2 – Fan 5	CE 1H and CE 2H for Fan 2 – Fan 5
5	Switch to vertical orientation and test Fan 1 – Fan 5 one last time	CE 3V for Fan 1 – Fan 5
6	Switch to back to horizontal orientation and test Fan 1 – Fan 5 one last time	CE 3H for Fan 1 – Fan 5

In all tests performed, specific attention was given to the trend of CE with time to ensure a steady-state CE was achieved. The test procedure for one of the hoods tested is broken down for clarity below:

1. Install range hood and set to desired speed (lowest or highest setting on range hood)
2. Heat ‘Top Surface’ to the ASTM specified surface temperature of 160 ± 10°C
3. Introduce CO2 tracer gas at 0.5% of range hood airflow rate

4. Wait until chamber undergoes 4 air changes
5. Take a minimum of 10 sets of measurements of three concentrations (C_exhaust, C_chamber, C_inlet), meaning that a set is made up of three measured values of the three different concentration values.
6. Plot the CE for each set of measurements and continue taking sets of measurements until the slope across the most recent 10 CE values has a magnitude less than 0.15 (i.e. less than 1.5% change in CE across all 10 measurements). See Appendix F for reference plot.
7. Take the last 10 of measurements and calculate an average value for each of the three concentrations, then use Equation 1 to calculate one final CE value, indicating that the CE test is complete.
8. Open door after the test is complete and clear out the test chamber until the difference between C_chamber and C_inlet is less than 50 ppm.
9. Keep range hood running at set speed and repeat steps 3 – 7 to calculate CE for *Test 2* while making sure that the surface is at the test temperature.
10. Dismount range hood and repeat steps 2 – 9 until all five range hoods analyzed in this study have been tested twice (*Test 1* and *Test 2*)
11. Change test chamber discharge orientation from vertical to horizontal and repeat steps 1 – 10.
12. Change test chamber discharge orientation from horizontal to vertical and perform one last vertical CE test (*Test 3*) on all five range hoods.

13. Change test chamber discharge orientation from vertical to horizontal and perform one last horizontal CE test (*Test 3*) on all five range hoods.

Test Scenarios

As noted previously, the five under the cabinet (UTC) range hoods tested in this study have the same width and design that is typical of residential wall-mounted range hoods. A representation of the UTC range hood profile and a photo of one of the range hoods tested is shown in Figure 47.

Figure 47: Typical under the cabinet (UTC) range hood analyzed in discharge orientation study

In total 60 different CE tests were performed on 20 unique test scenarios. Table 13 shows a breakdown of all the test scenarios performed in this study.

Table 16: Test scenarios performed in discharge orientation study (27in. mounting)

Fan ID	Speed Setting	Airflow rate (cfm)	Discharge Orientation
FAN 1	High	250	Horizontal, Vertical
	Low	130	Horizontal, Vertical
FAN 2	High	260	Horizontal, Vertical
	Low	120	Horizontal, Vertical
FAN 3	High	310	Horizontal, Vertical
	Low	120	Horizontal, Vertical
FAN 4	High	290	Horizontal, Vertical
	Low	160	Horizontal, Vertical
FAN 5	High	300	Horizontal, Vertical
	Low	160	Horizontal, Vertical

Results

Multiple factors have been proven to influence the capture efficiency (CE) and CE repeatability/reproducibility. Examples of factors that can influence CE include, but are not limited to, range hood characteristics (e.g. mounting height, flow rate, etc.) as well as test facility characteristics (e.g. inlet, tracer gas emitters, burner placement, etc.). However, in support of this study, there have not been any previous studies that investigate the effects of range hood discharge orientation (i.e. vertical vs. horizontal) on CE. In fact, all previous studies that utilized a test procedure based on controlled flow rate of a tracer gas through custom emitters, as found in ASTM-E3087.18, were done solely for vertical discharge orientations. To fill this gap, the following four sub-sections present the influence of discharge orientation on CE by testing in accordance with ASTM-E3087.18 five range hoods of similar design using a 27in. mounting height at both the high speed (HS) and low speed (LS) setting. Additionally, each of the five range hoods was tested three times at HS and three times at LS, with two tests being performed back-to-back, and the third test being performed after a mandatory dismount/remount. The first sub-section presents the effects of discharge orientation on CE, as well as the uncertainty in CE (δ) that is determined by using the precision and bias procedure outlined in ASTM-E3087.18. The second sub-section presents the results for CE repeatability by analyzing ΔCE, which is a measure of the variation between CE tests performed back-to-back, as well as the standard deviation (σ) between the 10-measurements that are averaged in order to determine CE, as specified by the ASTM. The third sub-section presents how the discharge orientation influences the CE reproducibility, which is indicated by the two reproducibility metrics α and β. Finally, the influence of range hood discharge orientation on the variation between tested performed multiple times is investigated by analyzing the differences in the variability metric (ε) for both orientations.

Effects on Average CE and CE uncertainty

The influence of discharge orientation on capture efficiency (CE), as well as the uncertainty in CE, was investigated by testing each of the five range hoods multiple times using both vertical and horizontal orientations. Each of the five range hoods was tested three times in accordance with ASTM-E3087.18 at the high speed (HS) and low speed (LS), using both vertical (vert.) and horizontal (hor.) discharges, which resulted in a total of 20 unique test scenarios (i.e. range hood, speed and discharge orientation) and a total of 60 tests. Figure 48 shows the average CE between the three tests performed at each test scenarios, with the error bars showing a range of +/-1 standard deviation.

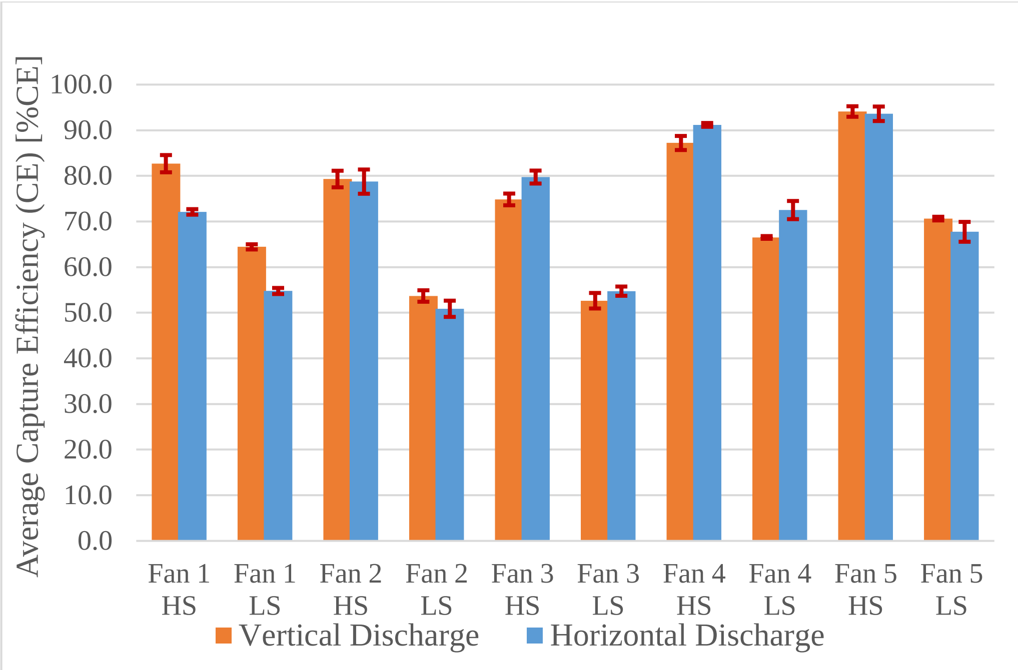


Figure 48: Average CE for 20 unique test scenarios analyzed in discharge orientation study. Error bars represent +/-1 standard deviation.

The results in Figure 48 show that for the 10 possible comparisons between horizontal and vertical discharge, 60% of the comparisons show a significant difference in CE, with significant difference between two tests being indicated by no overlap between the +/- 1 standard deviation ranges. The average value for the significant differences in CE (δCE) is 5.9%CE. Table 14 shows the significant changes in CE (δCE) when changing discharge orientation for the 10 possible tests comparisons analyzed in this study.

Table 17: Significant changes in CE (δCE) when changing discharge orientation for 10 possible tests comparisons of discharge orientation study

	Vertical → Horizontal	
	Inc. or dec.	δCE (%CE)
Fan 1 - HS	↓	**10.6**
Fan 1 - LS	↓	**9.7**
Fan 2 - HS	↔	**0.6**

Table 18 (continued): Significant changes in CE (δCE) when changing discharge orientation for 10 possible tests comparisons of discharge orientation study

Fan 2 - LS	↔	**2.8**
Fan 3 - HS	↔	**4.9**
Fan 3 - LS	↑	**2.1**
Fan 4 - HS	↑	**4.0**
Fan 4 - LS	↑	**6.0**
Fan 5 - HS	↔	**0.5**
Fan 5 - LS	↓	**2.9**

Table 14 shows that for the 60% of cases that have a significant change in CE when changing from vertical to horizontal discharge, half of these changes showed an increase in CE when switching from vertical to horizontal, while the other half showing a decrease in CE. Additionally, when the results showed no significant change in CE, the average deviation between horizontal and vertical CE was 2.2%CE, which is just outside the range of uncertainties typically experienced in this study. Thus, it can be concluded that the discharge orientation sometimes has a significant effect on CE and sometimes it does not, with specific range hood details (i.e. specific curvature, fan type, fan placement in housing, etc.) likely causing discrepancy between fans, meaning some fans having better CE performance in horizontal and some fans having better CE performance in vertical).

Additionally, the effects of discharge orientation on the CE uncertainty was also investigated. The results in Figure 49 show the results for CE uncertainty for the 10 range hood configurations (i.e. range hood model and speed) tested in this study of discharge type on CE.

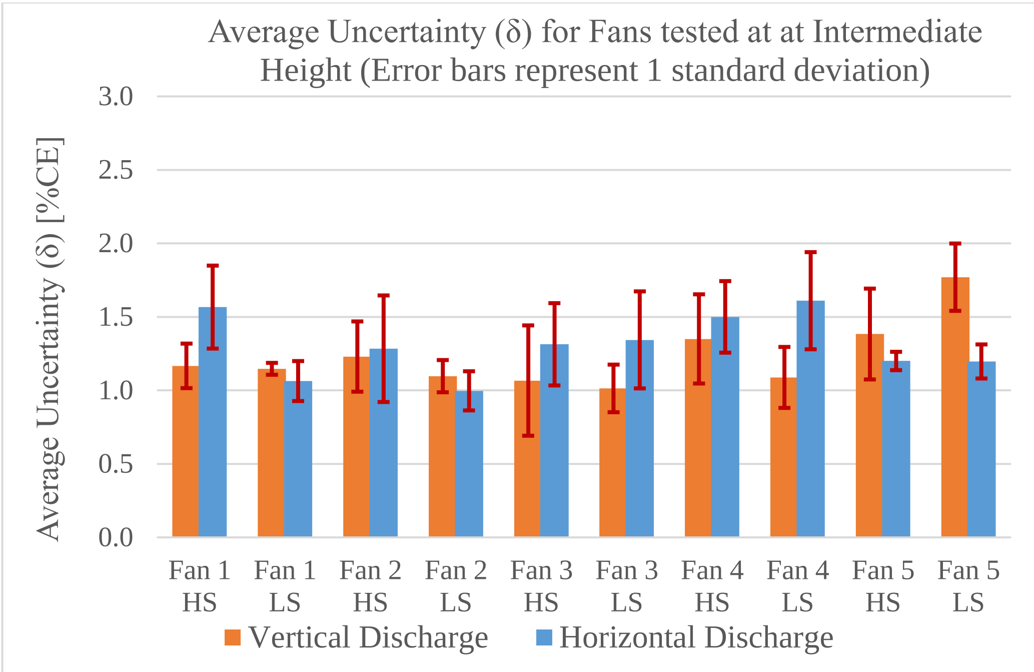


Figure 49: Average Uncertainty (δ) for 20 unique test scenarios analyzed in discharge orientation study. Error bars represent ±1 standard deviation.

The results in Figure 49 show that out of 10 possible comparisons, only one case showed a significant difference in CE uncertainty (δ), with the difference between the average δ for this case being less than 1.0%CE. Additionally, since all values for δ were typically less than 2.0%CE and always less than 2.5%CE for all cases independent of orientation, it can be concluded that the discharge orientation does not have a significant effect on the CE uncertainty.

<u>Effects on CE Repeatability</u>

The influence of range hood discharge orientation on CE repeatability was determined by analyzing two different metrics, namely the standard deviation between the last 10 CE measurements of a specific test (σ) and the repeatability metric ΔCE defined as the difference between consecutive CE tests, without a dismount and remounted. Figure 50 shows the average σ value for all the fans tested at an intermediate height.

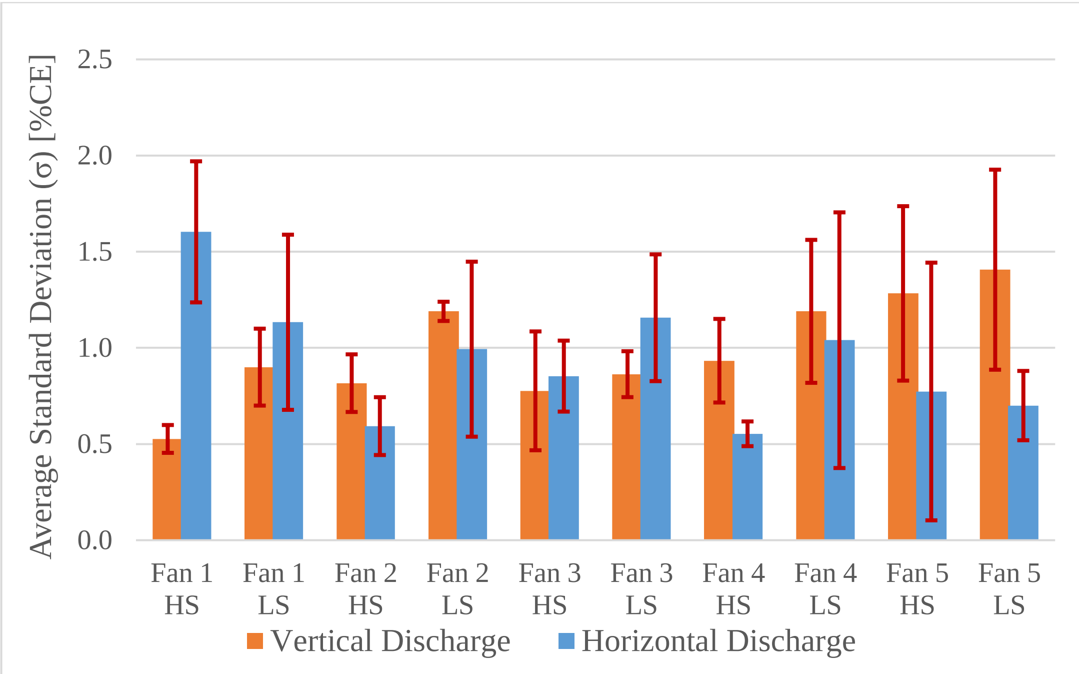


Figure 50: Average Standard Deviation (σ) for 20 unique test scenarios analyzed in discharge orientation study. Error bars represent ±1 standard deviation.

The results in Figure 50 show that the standard deviation (σ) was less than 2.0%CE for all tests performed, which is consistent with previous studies. Additionally, out of 10 possible comparisons, only 2 of them show a significant difference in standard deviation, with the maximum significant difference being 1.1%CE. Since the maximum significant difference of 1.1%CE is within the maximum uncertainty of 2.0%CE experienced in this study, it was concluded that the discharge orientation has little effect on the CE repeatability as indicated by the standard deviation (σ). As another means of quantifying CE repeatability, the repeatability metric ΔCE was used, which shows the absolute difference between CE tests performed consecutively for a specific test configuration. The results for ΔCE for all tests performed in this study are shown in Figure 51.

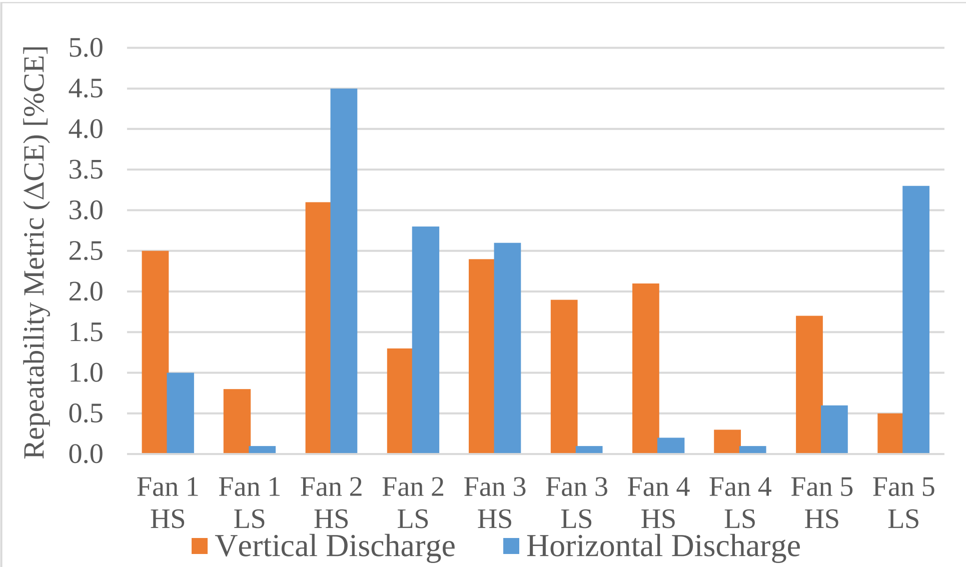


Figure 51: Repeatability Metric (ΔCE) for 20 unique test scenarios analyzed in discharge orientation study. Error bars represent ±1 standard deviation.

Figure 51 shows out of 10 possible comparisons, six show the vertical discharge to have poorer repeatability performance than the horizontal discharge, with a maximum increase in ΔCE of 1.9%CE, which is within the typical uncertainty found in this study. However, when the horizontal discharge case showed a higher ΔCE, the increase in ΔCE was as high as 2.8%CE, which greater than the 2.0%CE uncertainty typically experienced in this study.

Additionally, one of the range hoods tested (Fan 2 – LS) had a ΔCE value of 4.5%CE, which is greater than the typical range of uncertainty. After closer investigation, it was concluded that the reason for this high ΔCE for Fan 2 – LS is likely due to the fact that there was a 'CO_2 pocket' forming in the exhaust duct, making it difficult for the LS range hood to achieve a consistent concentration of CO_2 in the exhaust. Evidence of the

CO_2 pocket explanation is that the CO_2 concentrations were observed to fluctuate constantly during tests, and more so when comparing tests, which could be due to two additional bends and a Y-fitting causing various pockets/bends for CO_2 to accumulate. Therefore, it was concluded that the horizontal discharge orientation can sometimes lead to decreased repeatability performance for LS range hoods, especially if proper measures are not taken to ensure no CO_2 pockets form in the exhaust duct. The schematic in Figure 52 shows a diagram of the range hood in horizontal orientation with the primary CO_2 pocket in the exhaust duct circled.

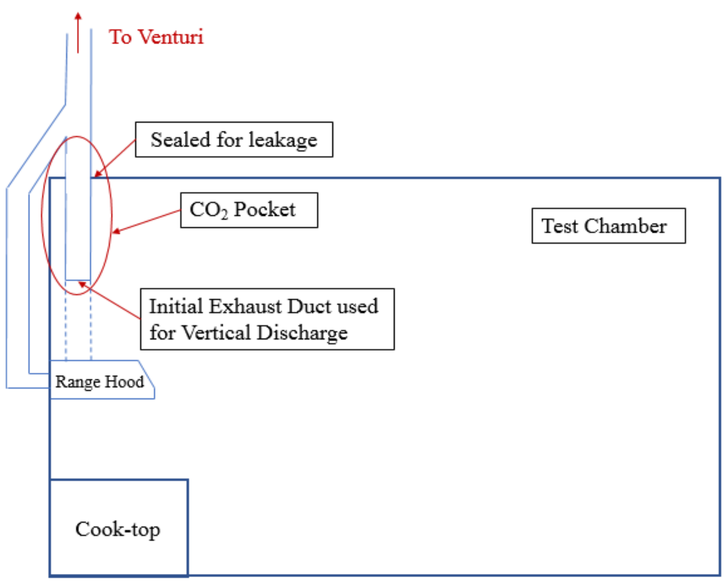


Figure 52: Range hood in horizontal orientation with CO2 pocket highlighted

However, since only one test unit showed a ΔCE value greater than 4.0%CE, it was concluded that the discharge orientation only has a minor effect on the CE repeatability.

Effects on CE Reproducibility

The effects of discharge orientation on CE reproducibility were investigated by analyzing the two reproducibility metrics, α and β, which represent the average and maximum discrepancy in CE, respectively, after a mandatory dismount/remount. Figure 53 presents the reproducibility metric α, which shows the average discrepancy in CE (i.e. the difference between CE3 and the average of CE1 + CE2) for the 20 range hood configurations analyzed in this study.

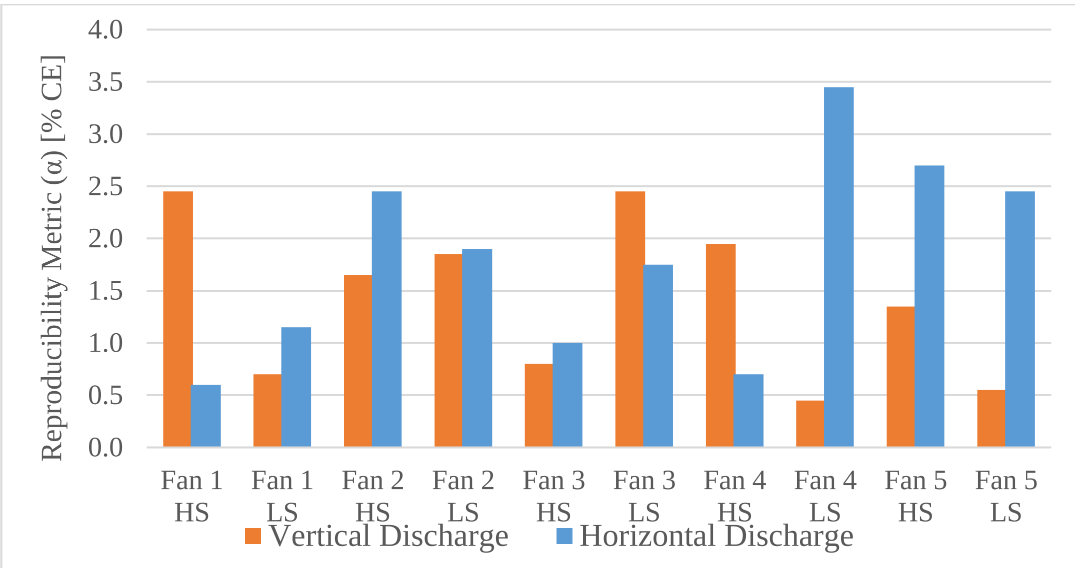


Figure 53: Reproducibility Metric (α) for 20 unique test scenarios analyzed in discharge orientation study. Error bars represent ±1 standard deviation.

The results in Figure 53 show that similar to previous studies, the maximum α value for all fans tested is vertical configuration is always less than 3.0%CE. It should be noted that all cases show an α value less than 3.0%CE except for one horizontal discharge case; namely 'Fan 4 – LS'. When comparing the difference in α values calculated using horizontal discharge versus vertical discharge for a specific range hood, the maximum discrepancy in α was 3.0%CE, which is outside the range of typical uncertainties experienced in this study. Furthermore, 70% of cases showed worsened reproducibility performance using the horizontal discharge. Additionally, Figure 53 shows that the range for α is 0.5-2.5%CE for vertical discharges and 0.6%CE to 3.5%CE for horizontal discharges. Thus, it was concluded that the horizontal discharge orientation may result in worsened reproducibility performance.

Unlike previous studies, the α metric in this study has a smaller range than the ΔCE (i.e. repeatability) metric; which has a range of 0.3-3.1%CE and 0.1-4.5%CE for the vertical and horizontal configurations, respectively. It is believed that the CO_2 pocket mentioned in the repeatability section of this chapter is likely a cause for ΔCE being larger than α in this study. As another means to measure the reproducibility, the β metric was also calculated, which displays the maximum discrepancy between tests performed with a mandatory dismount/remount between tests. The results for the β metric are presented in Figure 54.

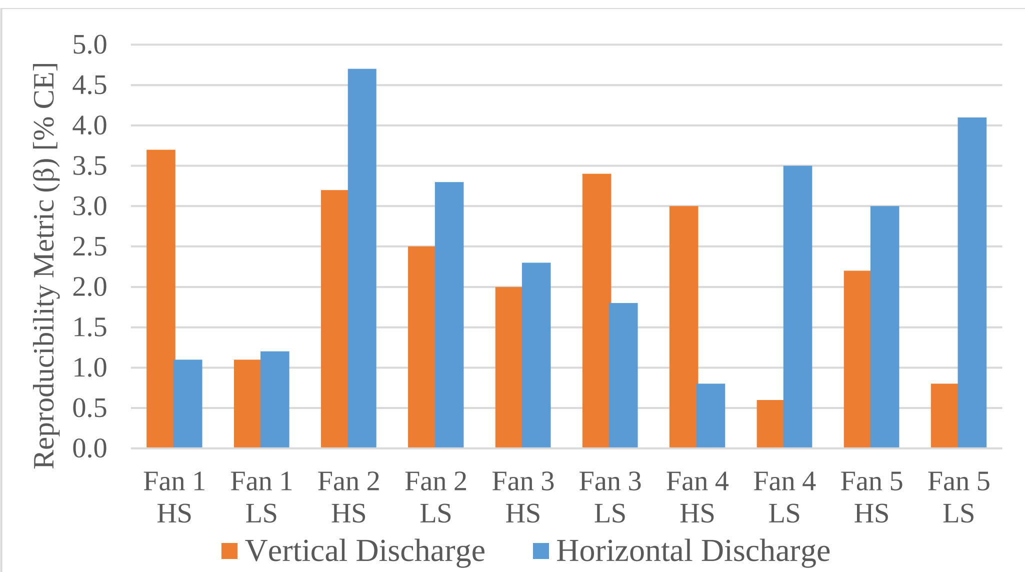


Figure 54: Reproducibility Metric (β) for 20 unique test scenarios analyzed in discharge orientation study. Error bars represent ±1 standard deviation.

The results in Figure 54 show that all β values are less than 5.0%CE, which is consistent with results from Chapters V – VI and again implies acceptable reproducibility between tests, as indicated by a CE within +/- 2.5%CE (i.e. the maximum uncertainty encountered in this study). 70% of cases show that reproducibility is worsened when changing from vertical to horizontal discharge. Additionally, similar to the α metric, the maximum discrepancy between β values when comparing vertical and horizontal discharge is 3.3%CE, which is outside of the maximum uncertainty in this study. Another important observation that is consistent with previous studies and important to note, is that the β metric always provides a higher, and thus more conservative value (i.e. larger range of expected reproducibility), for the CE reproducibility. Therefore, the β metric is favorable for describing reproducibility in future HVI/ASHRAE standards.

Effects on CE Variability

The effects of discharge orientation on capture efficiency (CE) variability was determined by analyzing the coefficient of variation, or ε metric, between the three CE tests performed using a specific test scenario (i.e. range hood, speed and discharge orientation). For reference, the ε metric is presented in Equation 11 of Chapter III. To reiterate, ε is a measure of the relative deviation expected for a specific test scenario with a certain CE value. Another interpretation of ε is that the ε is a measure of the deviation relative to the average CE value for that specific test scenario. Figure 55 presents the coefficient of variation, ε, for the 20 test scenarios analyzed in this study.

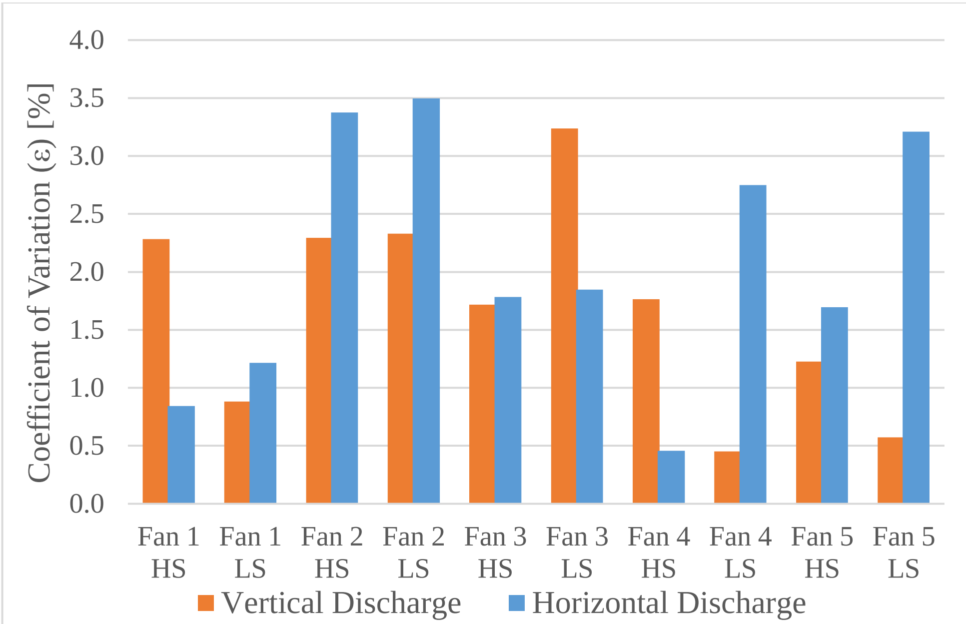


Figure 55: Coefficient of Variation (ε) for 20 unique test scenarios analyzed in discharge orientation study. Error bars represent ±1 standard deviation.

The results in Figure 55 show that 80% of cases have an ε value less than 3.0%, while all cases have an ε value less than 3.5%, which is consistent with the results from Chapters V – VI. It should also be noted that 70% of cases showed worsened variability performance (i.e. higher ε value) for tests run using horizontal discharge. Additionally, the maximum discrepancy between ε for vertical configuration versus ε for horizontal configuration was 2.6%, which is the difference between 0.6% and 3.2% or a 400% increase. Thus, it can be concluded that the discharge orientation can have a significant effect on the CE variability, dependent on range hood flow rate and other range hood characteristics (i.e. curvature, fan placement, etc.). However, the range of ε values for the vertical and horizontal discharges are 0.5-3.2%CE and 0.5-3.5%CE, respectively, indicating that both discharge orientations result in a similar range for variability.

Summary

Using a test facility built in accordance with ASTM-E3087.18, five range hoods were tested at a fixed mounting height of 27in. to compare the effects of discharge orientation on capture efficiency (CE), as well as CE repeatability, reproducibility and variability. The five range hoods were tested at both the high speed (HS) and low speed (LS), using both vertical and horizontal discharge, for a total of 10 possible comparisons. Results showed that significant differences in CE (i.e. no overlap in standard deviations) ranged from 2.1%CE to 10.6%CE, with an average value of 5.9%CE. For the 60% of cases that had a significant change in CE when changing from vertical to horizontal discharge, half of these changes showing an increase in CE when switching from vertical to horizontal, and the other half showing a decrease in CE. Thus, it was concluded that the discharge orientation can have a different effect on the range hood CE, with specific range hood details (i.e. curvature, fan type, fan placement, etc.) causing a discrepancy between fans (i.e. some fans having better CE performance in horizontal and some fans having better CE performance in vertical). When investigating the effects of discharge orientation on CE uncertainty (δ) only one case showed a significant difference in δ, with the difference in δ being less than 1.0%CE. Therefore, it was concluded that the discharge orientation does not have a significant effect on the CE uncertainty.

The effects of discharge type on CE repeatability was determined by analyzing the standard deviation taken (σ) between the last 10-measurements, as well as the repeatability metric (ΔCE), which represents the absolute difference between CE tests performed back-to-back. In all cases, the standard deviation (σ) was less than 2.0%CE

for both orientations, with the maximum significant difference being 1.1%CE. Since the maximum significant difference in σ was less than the maximum uncertainty of 2.0%CE experienced in this study, it was concluded that the discharge orientation has no effect on the standard deviation (σ). Investigation of the ΔCE repeatability metric, yielded dissimilar results with tests showing changes in ΔCE greater than 2.0%CE (e.g. 2.8%CE). Additionally, one of the range hoods tested (Fan 2 - LS) tested using horizontal configuration showed a ΔCE value of 4.5%CE that was greater than the typical range of uncertainty (i.e. +/- 2.0%CE). After closer investigation, it was concluded that the reason for the high ΔCE for this LS, horizontal discharge case, was due to the exhaust duct design having a large 'CO2 pocket' forming in the exhaust duct, which caused the low speed range hood to have inconsistent CO2 concentration in the exhaust duct.

In investigating the effects of range hood discharge on CE reproducibility the two reproducibility metrics, α and β, were analyzed. Results showed that the maximum discrepancy in α calculated using horizontal discharge versus vertical discharge for a specific range hood was 3.0%CE (i.e. outside the range of CE uncertainty experienced in this study). Additionally, 70% of cases showed worsened reproducibility performance using the horizontal discharge. Investigation of the reproducibility metric β showed that all β values are less than 5.0%CE, and the maximum discrepancy between β values when comparing vertical and horizontal discharge is 3.3%CE. Similar to α, 70% of cases show β increases (i.e. reproducibility is worsened) when changing from vertical to horizontal discharge. Thus, it was concluded that the horizontal discharge orientation may lead to worsened reproducibility performance.

Results for variability showed that 80% of cases had a coefficient of variation (ε) value less than 3.0%CE and all cases had an ε value less than 3.5%CE, which is consistent with the results from the two previous Chapters. Furthermore, 70% of cases showed worsened variability performance (i.e. higher ε value) for tests run using horizontal discharge. Thus, it can be concluded that the discharge orientation can have a significant effect on the CE variability, depending on range hood flow rate and other range hood characteristics (i.e. curvature, fan placement, etc.). However, the range of ε values for the vertical and horizontal discharges are 0.5-3.2%CE and 0.5-3.5%CE, respectively. These results indicate that although some fans may perform worse using a specific discharge orientation, both discharge orientations result in a similar range for variability.

CHAPTER VIII

A MODEL FOR DETERMINING CAPTURE EFFICIENCY USING COMPUTATIONAL FLUID DYNAMICS

Overview

There are currently no HVI/ASHRAE standards that present a specific method for determining the capture efficiency (CE) of household kitchen rangehoods. Furthermore, there are various factors that can influence the capture efficiency (CE) of domestic range hoods. Although the American Society of Testing and Materials (ASTM) recently developed a test standard (ASTM-E3087.18), this standard requires the design and construction of a simulated test kitchen with corresponding exhaust duct in order to perform CE testing. In that regard, experimental CE testing in accordance with ASTM-E3087.18 can be time consuming and costly. Additionally, depending on range hood flow rate, some CE test can take as long as 7-8 hours to complete, with additional time given to allow the cook-top to reach the desired temperature specified by ASTM-E3087.18. Therefore, in an effort to reduce the time for a full investigation of the factors influencing CE, a simplified model for determining CE was developed herein using Fluent, a computational fluid dynamics (CFD) software package. The CFD model consists of a two-phase model, with phase 1 being air and phase 2 being the tracer gas (CO2). Boundary conditions were imposed on the CFD model that were based on experimental observations as well as ASTM specific constraints. Finally, the chamber CO2 concentration was measured using two methods; namely, at the precise point in the chamber specified by ASTM-E3087.18, as well as the volume average of CO2 in the entire chamber. Measurement of CO_2 concentration using two methods was done in order to compare the CO_2 concentration determined using the ASTM chamber placement with the simulated volume average CO_2 concentration determined by the CFD software.

Problem Statement

There have been reports of research done to develop a computational model that is capable of producing a CE metric consistent with the experimental methods presented in the ASTM test standard for measuring CE (ASTM-E3087.18). It should be noted that the ASTM-E3087.18 requires the design and construction of a simulated test kitchen with specific leakage requirements and an exhaust duct capable of measuring range-hood flow rates with 5% accuracy. In that regard, CE testing of range hoods in accordance with ASTM-E3087.18 can be costly and require significant amounts of labor hours. Although an experimental test method for determining range hood CE was recently developed by the ASTM, and the studies presented in this dissertation will support the promulgation of this standard to other governing bodies, the experiments used to develop ASTM-E3087.18 are primarily based on experiments from one test facility. Furthermore, based on experiments performed in this study, a single CE test can take as long as 7-8 hours, with extensive wait times attributed to: emitter plates reaching 160C, the chamber undergoing four air changes (specifically with a low flowrate range hood) and CE measurements reaching steady-state. Therefore, there is a need for a CE model that can provide CE results consistent with ASTM-E3087.18 but is less costly and time consuming. This chapter describes a CE model developed using computational fluid dynamics (CFD), which is capable of providing CE results that are consistent with ASTM-E3087.18.

Computational Analysis

A computational fluid dynamics (CFD) model was developed using Fluent v19.0, flow simulation software. In this CFD analysis, a 3D model of the 'control volume' of air in the chamber was modeled using SolidWorks 2019 and imported into Fluent. After the 'control volume' was imported, a 'mesh' was applied to the entire volume with specifications provided by the user. The mesh was used to discretize the control volume into several individual elements that were used to perform a finite difference thermal, fluid and species transport analysis. Next, various constraints referred to as 'boundary conditions' were placed on the walls surrounding this air volume as well as the inlet/exhaust to the control volume. Of special importance in this computational analysis is the need to define two separate species, namely CO2 and air, such that the concentration of CO2 at the various positions specified by ASTM-E3087.18 can be measured in order to determine CE. In addition to specifying boundary conditions on the species concentrations, specifically at the inlet to the chamber, it is also important to define how these two species interact with one another (i.e. density, surface tension, etc.). The following sub-sections describe the steps taken to create a CFD model for CE, along with a presentation of results and discussion.

Defining Control Volume

The first step in the computational fluid dynamics (CFD) analysis is defining a control volume that simulates the air in a test chamber. In order to do this an exact replica of the capture efficiency (CE) test chamber was modeled using SolidWorks 2019 software and then the 'Add/Subtract' feature of SolidWorks was used to subtract the CE test chamber volume from a solid cube. A cross section of the CE test chamber modeled using SolidWorks is shown in Figure 56.

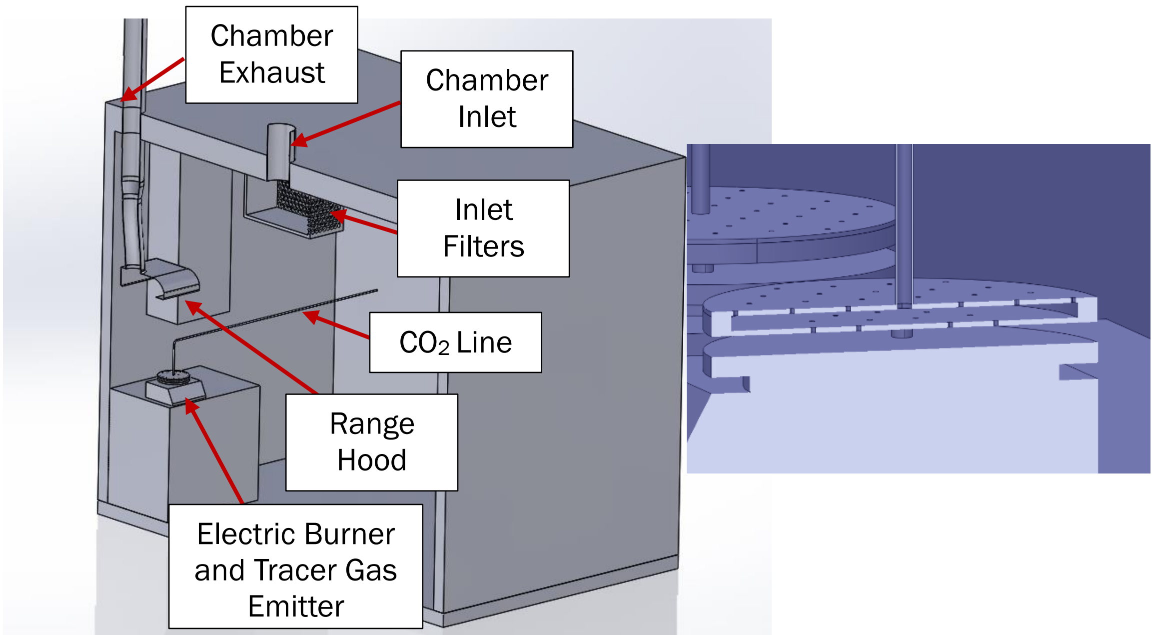


Figure 56: Cross sectional area view of CE test chamber (left) and ASTM specified emitter plates (right)

Some important features on the SolidWorks model, which is shown in Figure 56, are defining of the filter holes on the inlet, modeling all the curves/bends of both the range hood and the exhaust system and finally modeling the tracer gas emitter plates as specified by the ASTM. Initially when this air volume was meshed using the Fluent software and proper boundary conditions were applied, several reverse flow warnings were output by the software that resulted in non-converging solutions. Additionally, the total calculation time was in excess of 70 hours, which would prove to be less time efficient than the CE experiments themselves. Therefore, a simplified model of the CE test chamber was modeled in SolidWorks, prior to being imported into Fluent, and is shown in Figure 57.

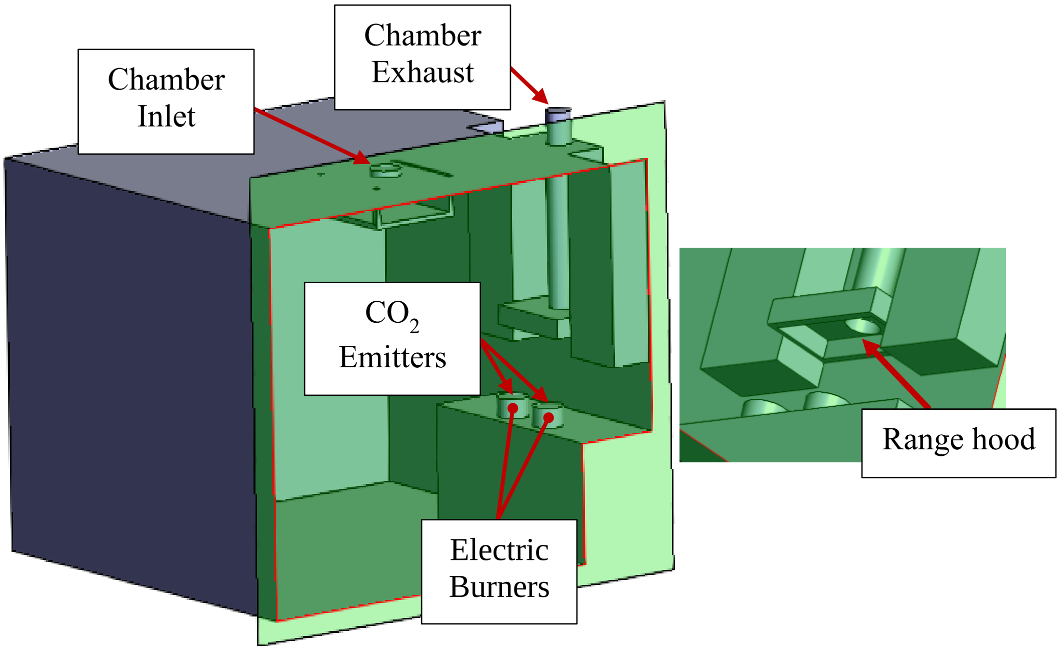


Figure 57: Simplified 3D Model of CE Test Chamber (left) and simplified range hood (right)

Some important features in the Figure 57 simplified approach is that the filters on the chamber inlet have been removed and certain details of the range hood/exhaust system were altered. It should be noted, however, that the depth and width of the range hood remained constant. Additionally, the CO_2 emitters were simplified into a cylinder of equivalent diameter to the CO_2 emitter, which is specified by the ASTM, and with a height that lines up with the top of the CO_2 emitters when they are placed on the electric burners. To reiterate, the air volume was extracted from this 3D model using the 'Add/Subtract' feature of SolidWorks and then imported into Fluent.

Defining Mesh

The next step in the computational analysis is to define a mesh for the 3D model, which in essence breaks up the air volume into several smaller elements that are used in a finite element solver specified in the next sub-section. The primary criteria used for this mesh is an average element size of 20cm (7.8in). Applying this mesh criteria to the control volume described in the previous section resulted in a total of 4,078,253 elements that had a minimum size of 2cm (0.8in) and a maximum length of 40cm (15.7in). The characteristic lengths described are those specific to the equilateral triangles that make up the tetrahedral elements that are used in this mesh. An image of the mesh described herein applied to the control volume is shown in Figure 58.

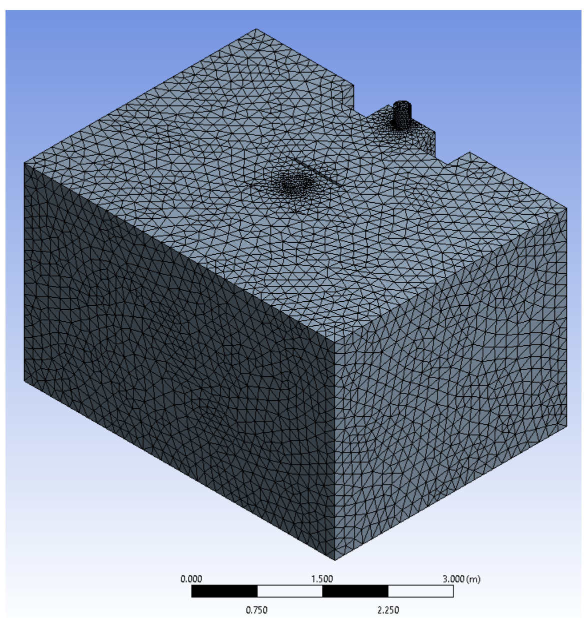


Figure 58: Mesh used in computational analysis

Solver Settings and Boundary Conditions

The solver described in this sub-section uses numerical methods and built-in algorithms to solve complex fluid mechanics, heat transfer, mass transfer and chemical reaction problems. The numerical methods used by Fluent involve utilizing partial differential equations (PDE) that describe fluid flow, heat transfer, mass transfer and chemical reactions, numerically discretizing them based on the elements in the mesh and solving the PDE algebraically. The solver methods used by Fluent, and other CFD software, are valuable since they can provide insight on the real-world flow behavior of different scenarios, thus saving time/money associated with experiments. The specific solver settings and energy models used in this computational analysis are outlined in Table 14.

Table 19: Solver settings defined in Fluent

Parameters	**Definition**
Solver	Pressure-based, steady-state, double precision
Viscous Model	K-epsilon (2-eqn), multiphase turbulence model treated as separate phases
Energy Model	Turned On
Multiphase Model	Eulerian with Air (phase 1) and CO_2 (phase 2) both treated as incompressible fluids
Phase Interactions	Surface tension (constant)= 0.23 N/m

The Energy Model used in this computational analysis, which considers both viscous and thermal forces, is shown in Equation 12 and is applied to each phase (air and CO_2) individually.

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\vec{v}(\rho E + p)) = \nabla \cdot \left(k_{\text{eff}} \nabla T - \sum_j h_j \vec{J}_j \right) \tag{12}$$

where ρ is the density of the specific phase, v is the velocity of that phase in a specific mesh element, p is the pressure of the fluid in a specific mesh element, k_{eff} is the effective thermal conductivity (which considers turbulent effects), T is the temperature of a specific mesh element, h_j is the sensible enthalpy and J_j is the diffusion flux of the species. All variables use the International System of Units (SI) and are based in kilograms, meters and seconds. It should also be noted that the surface tension between air and CO_2 of 0.23N/m was determined by taking the middle value of the range of 0.01N/m to 0.45N/m found in open literature (Liu 2016, Chow 2015, Nielsen 2012 and Chalbaud 2010).

Some boundary conditions based on the experimental scenario being replicated are outlined in Table 15.

Table 20: Boundary conditions applied to various locations in CE test chamber

Location	Boundary Conditions
Chamber Inlet	Type: **Pressure inlet** Pressure: **0Pa (gage) –** *Atmospheric pressure* CO_2: **0.00042 –** *420ppm atmospheric concentration*
Chamber Exhaust	Type: **Velocity inlet** Velocity: **- 4.31m/s (-14.1ft/s) –** *Range hood flowrate* Pressure: **-5Pa (gage)** – *Maximum ASTM depressurization*
CO_2 Inlet	Type: **Mass flow inlet** Setting: **0.001kg/s (30L/min) (CO_2)** – *ASTM Requirement*
Cook-top	Type: **Wall (surface)** Setting: **160˚C fixed temperature** – *ASTM Requirement*

It should be noted that the italicized text in Table 15, describes the justification for each of the boundary conditions applied. Also, for reference, the chamber inlet, chamber exhaust, CO2 emitters and electric burners referenced in Table 15 are those presented previously in Figure 57**.**

In all simulations performed, 5,000 iterations were run and the solver was required to output a velocity flow field, pressure contour and CO_2 distribution in the chamber. Also, since American Society of Testing and Materials (ASTM) specifies measuring the CO_2 in the exhaust, inlet and in chamber, the area weighted average in all these locations was also outputted and recorded. The concentration of CO_2 in the chamber were found by using two different approaches, with one being the area weighted average was taken at the precise location specified by the ASTM and the second based on taking the volume weighted average of the entire chamber. In all CE calculations reported herein, the area weighted average of the chamber at the ASTM specified location is the primary CO_2 concentration used to measure CE and the volume weighted average of the chamber is a secondary CO_2 concentration to verify the accuracy of the primary measurement.

Results

This section presents the results for the velocity flow field, pressure contour, CO2 distribution and capture efficiency (CE) for several different cases. Additionally, this section outlines some additional steps taken to refine the CO_2 emitters based on large discrepancies observed between the experimental/simulated CO_2 concentrations and the CO_2 contours in the test chamber that were output by the computational fluid dynamics (CFD) simulation.

<u>*Initial Results*</u>

This sub-section presents the results for the velocity flow field, pressure contour and CO_2 distribution for the initial computational fluid dynamics (CFD) simulation. Additionally, this sub-section describes some of the observations made using the initial CFD simulation followed by the steps taken to refine the CFD simulation based on these observations. It should be noted that none of the steps taken to to refine the CFD model influenced the velocity flow field and pressure contour that are described at the beginning of this sub-section.

Velocity Flow Field

The velocity flow field for the simplified CE test chamber that was output using the computational fluid dynamics (CFD) model is shown in Figure 59**.**

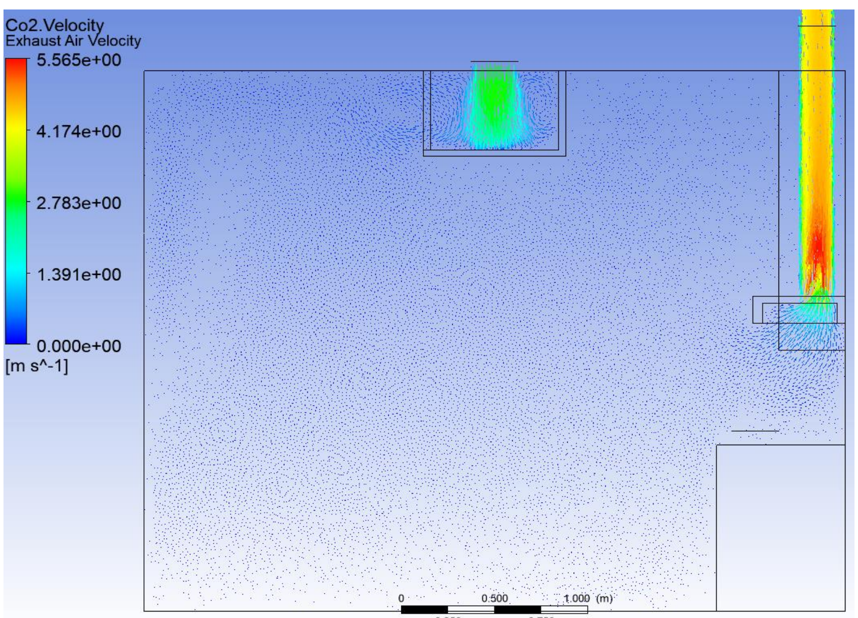


Figure 59: Velocity flow field output using CFD model

Some key observations that can be made from Figure 59 are the fact that the highest magnitude of velocity is immediately upstream from the range hood even though the boundary condition placed on the exhaust was placed at the end of the exhaust duct (i.e. the portion sticking out of the chamber). Additionally, there is some recirculation observed at the inlet to the chamber due to the deflector plate that is required by the ASTM. As a consequence of this deflector plate, there is minimal airflow throughout a majority of the chamber; which is likely the ASTM intent as well. In calculating the volumetric flowrate at the chamber outlet and chamber inlet, the values were 300cfm (0.1415m^3/s) and 299cfm (0.1414m^3/s), respectively, which is a difference of 0.3% at worse. Therefore, it was concluded that the pressure boundary condition prescribed at the inlet and the velocity condition prescribed at the outlet provides an accurate representation of the flow coming in and out of the chamber (i.e. the volumetric flow rate coming into the chamber is equivalent to the volumetric flow rate being exhausted out of the chamber).

Pressure Contour

The pressure contour within the simplified CE test chamber that was output using the computational fluid dynamics (CFD) model is shown in Figure 60**.**

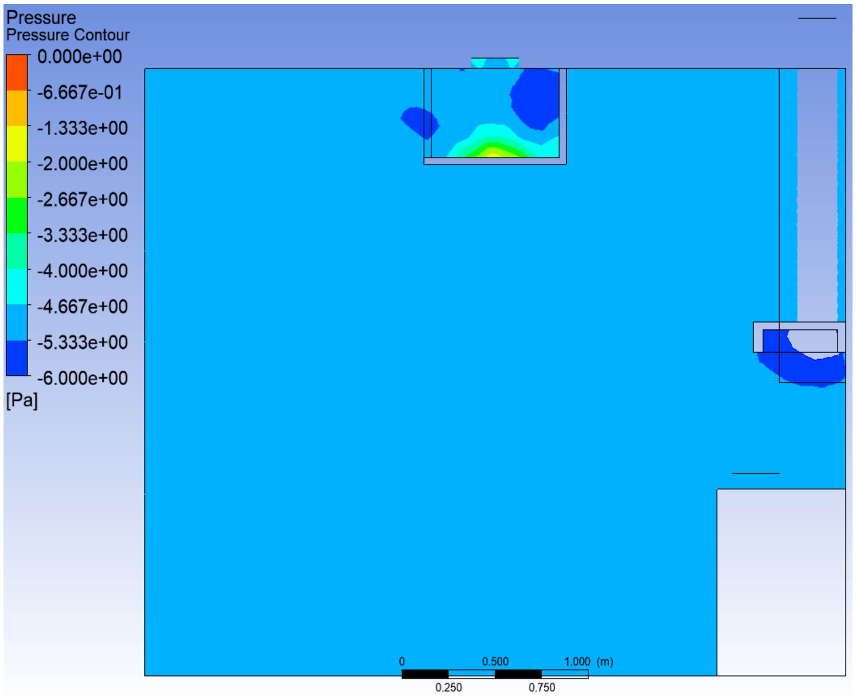


Figure 60: Pressure contour output using CFD model

Some key observations that can made by analyzing the results in Figure 60 is that the highest magnitude of pressure is at the inlet to the range hood. In fact, the pressure at the inlet to the range hood has a magnitude of 5.3Pa, which is greater than the ASTM specified limit of 5Pa. However, most of the chamber is below the maximum depressurization of 5Pa with a magnitude of 4.7Pa. Another key observation is that there is a stagnation point observed at the chamber inlet due to the deflector plate that is required by the ASTM. It is also likely that the existence of this stagnation point is the intent of the ASTM, to prevent make-up air (i.e. air that is brought into the chamber as the range hood exhaust air out) from coming in with a high velocity and impinging directly on the cook-top. Specifically, the make-up air is dampened and distributed with a lower velocity throughout the chamber to prevent high velocity make-up air from disturbing the CO_2 flow patterns over the cook-top.

CO_2 Distribution and Capture Efficiency

After running the simulation, it was observed that the primary CO_2 concentration in the chamber, which is based on the ASTM specified location, was equivalent to the inlet CO_2 concentration. Additionally, a large discrepancy of 48% was found between the area weighted average concentration of CO_2 in the chamber and the volume weighted average concentration in the chamber (i.e. 420ppm vs. 620ppm). Furthermore, the concentration of CO_2 in the exhaust was over 8,000ppm, which was much higher than the exhaust concentrations observed in experiments (i.e. typically between 4,000 – 6,000ppm). The initial results for the different concentrations output by the computational fluid dynamics (CFD) simulation performed using Fluent are shown in Figure 61**.**

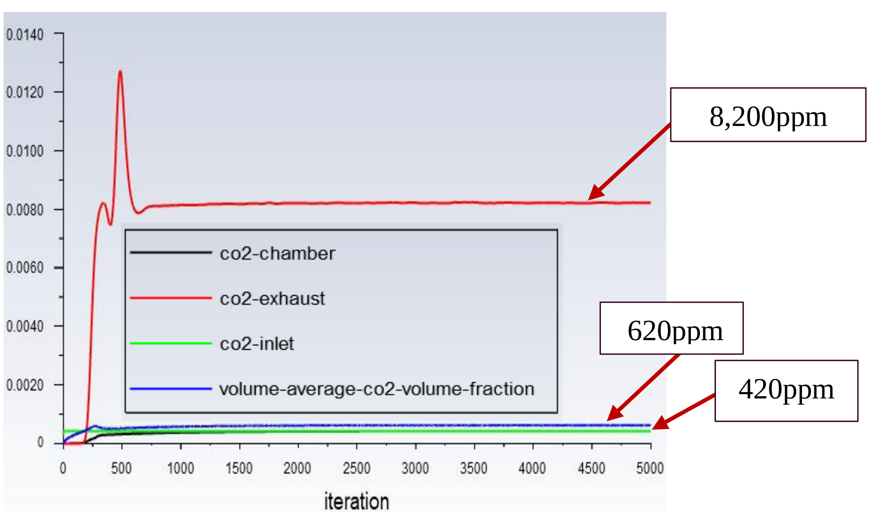


Figure 61: Results for various CO2 concentrations using initial CFD simulation

It should be noted that the capture efficiency (CE) determined using the primary chamber CO_2 concentration (i.e. that which is in accordance with the ASTM specified location) was calculated to be 100%, which is higher than anything observed in previous experiments or reported in the open literature.

Upon closer investigation of the CO_2 distribution in the test chamber, it was observed that the CO_2 was leaving the emitters and settling towards the cook top. Figure 62 shows the initial CO_2 distribution in the room with emphasis on the settling CO_2.

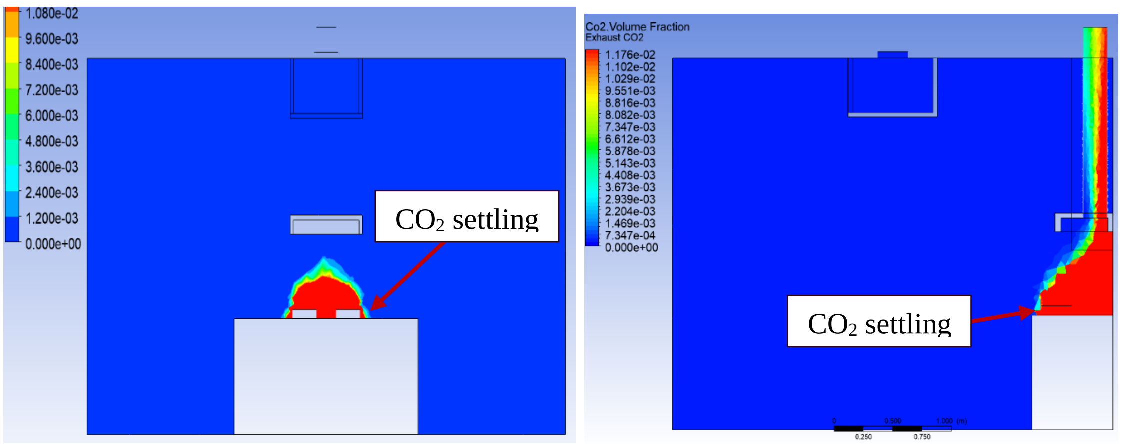


Figure 62: Initial CO2 distribution in the test chamber

Since the CO_2 boundary condition is specified as a mass flow rate, with constraints defined by ASTM (i.e. less than 0.5% of the range hood volume flow rate) and mass flow rate ($\dot{m}$) is defined as shown in Equation 13, the only way to increase the velocity (v) of the CO_2 tracer gas having constant density (ρ) is to reduce the area of the CO_2 emitters (A).

$$\dot{m} = \rho A v \tag{13}$$

Therefore, a new area (A) would need to be selected with a dimeter that is smaller than the 10in. diameter used in the initial model.

Refining CO_2 Emitters Based on Phase Distributions

A new area with a diameter of 0.32in. (0.01m) was selected for the emitters, with the size being determined by taking all the holes on the ASTM specified emitter plates and combining them into a single area and solving for the diameter. Once again, the simulation was run for 5,000 iterations and the CO_2 concentrations in the test chamber were output. Figure 63 shows the results for the CO_2 concentrations using the new emitters with 0.32in diameter.

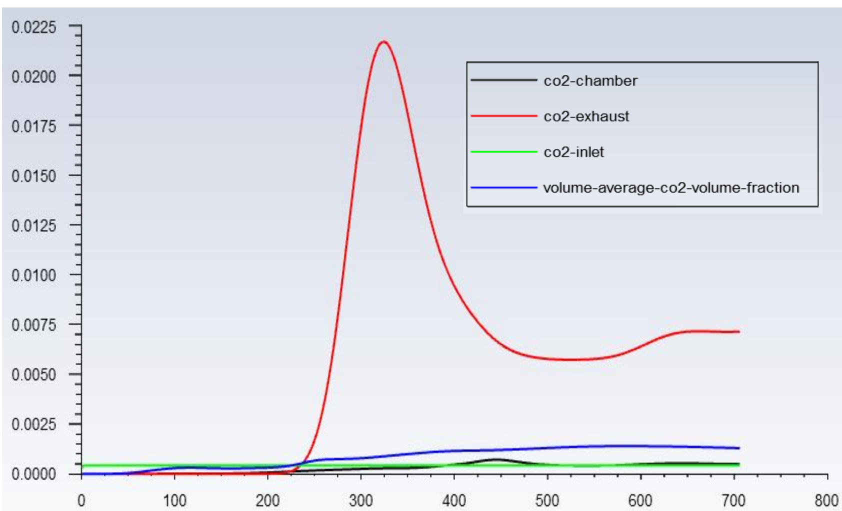


Figure 63:CO_2 concentrations output by simulation using 0.32in diameter emitters

Once again it was observed that there was a large discrepancy between the primary and secondary chamber concentrations of CO_2. Specifically, the primary and secondary chamber concentrations were 489ppm and 1,289ppm, respectively. Additionally, the CE calculated using the primary CO_2 concentration, as specified by the ASTM, was 98.9%, which is much higher than any CE observed in previous experiments or reported in the open literature. Additionally, the CE of 98.9% is much higher than the CE measured experimentally for the range hood being replicated in the CFD model (i.e. having equivalent depth, width and flowrate). It should be noted that the range hood with full details, which was originally modeled before simplification, has a CE of 77.9%. Therefore, the CO_2 contour was once again analyzed with the results shown in Figure 64.

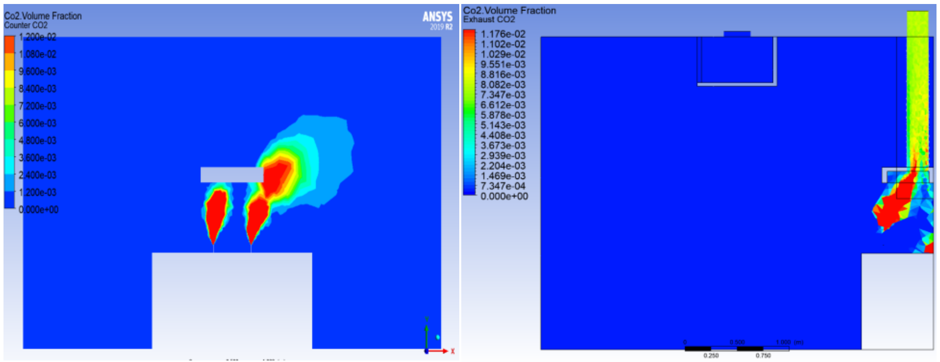


Figure 64: CO_2 contour output by simulation using 0.32in diameter emitters

The results in Figure 64 appear to show the CO_2 coming out of the emitters with such a high velocity that the CO_2 is blown right into the exhaust duct, and in some cases blowing past the range hood. Therefore, it was concluded that the CO_2 velocity coming out of the emitters was too high based on the emitter diameter of 0.32in (.01m) selected, and a middle-sized diameter was selected for the emitters. The emitter diameter of 2.75in. (0.07m) selected for this third case, is a value between the initial 10in. (0.25m) diameter and previous 0.32in. (0.01m) diameter used. For reference, the various diameters, areas and velocities modeled in this sub-section are presented in Table 17.

Table 21: Various diameters, areas and velocities used in CFD model

Case	Diameter	Area	Velocity
1	10in. (0.25m)	$78.8in^2$ ($0.051m^2$)	0.04ft/s (0.013m/s)
2	0.32in. (0.01m)	$.08in^2$ ($5.19e\text{-}05m^2$ or $0.519cm^2$)	41.5ft/s (12.6m/s)
3	2.75in. (0.07m)	$5.94in^2$ ($0.004m^2$)	0.56ft/s (0.17m/s)

Figure 65 presents the CO_2 concentrations output by the CFD simulation using Case 3, which is the 2.75in. diameter case.

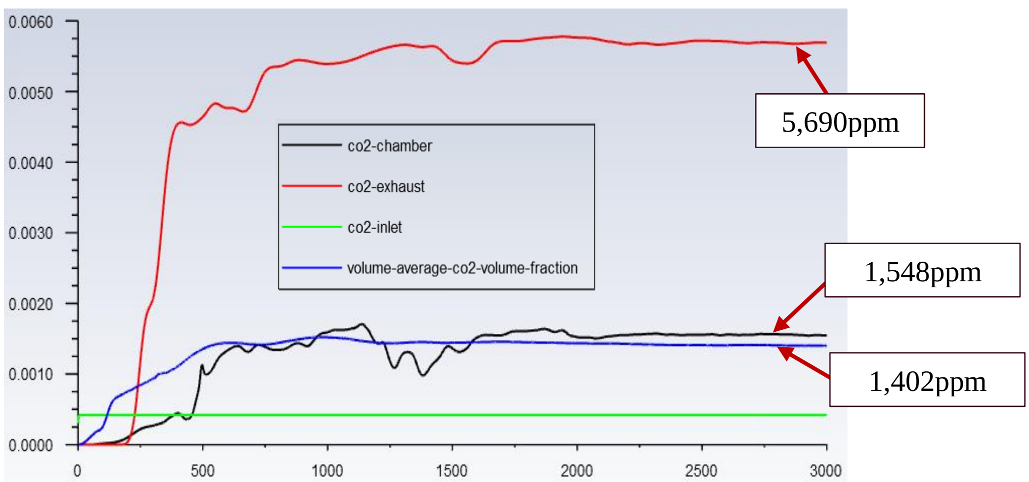


Figure 65: CO_2 Concentrations output by simulation using 2.75in. diameter emitters

As shown in Figure 65 there is strong agreement between the primary (ASTM) and secondary (volume weighted average) CO_2 concentrations in the chamber. The primary and secondary chamber concentrations were 1,548ppm and 1,402ppm, respectively, which is only a 9.4% difference. Additionally, the exhaust concentration was found to be 5,690ppm, which is within the typical range of 4000-6000ppm observed in experiments. Finally, the CE calculated using the primary and secondary CO_2 concentration was, 78.6% and 81.4%, respectively. The experimental CE for the range hood originally modeled (i.e. full details/curvature and exhaust flow rate of 300cfm) is 77.9%. Thus, both the absolute between the experimental CE and the primary CE modeled using CFD was less than 1.0%CE, and percent difference was less than 1.0%. Finally, varying the surface tension interaction between Phase 1 (air) and Phase 2 (CO_2) was found to have a significant effect on the CO_2 distribution in the room with the intermediate value for surface tension originally chosen (i.e. 0.23N/m), and shown below in Figure 66, giving the most accurate results for the primary CE versus the experimental CE. The results for the CO_2 distribution in the room using the other emitter sizes is shown in Appendix G for reference.

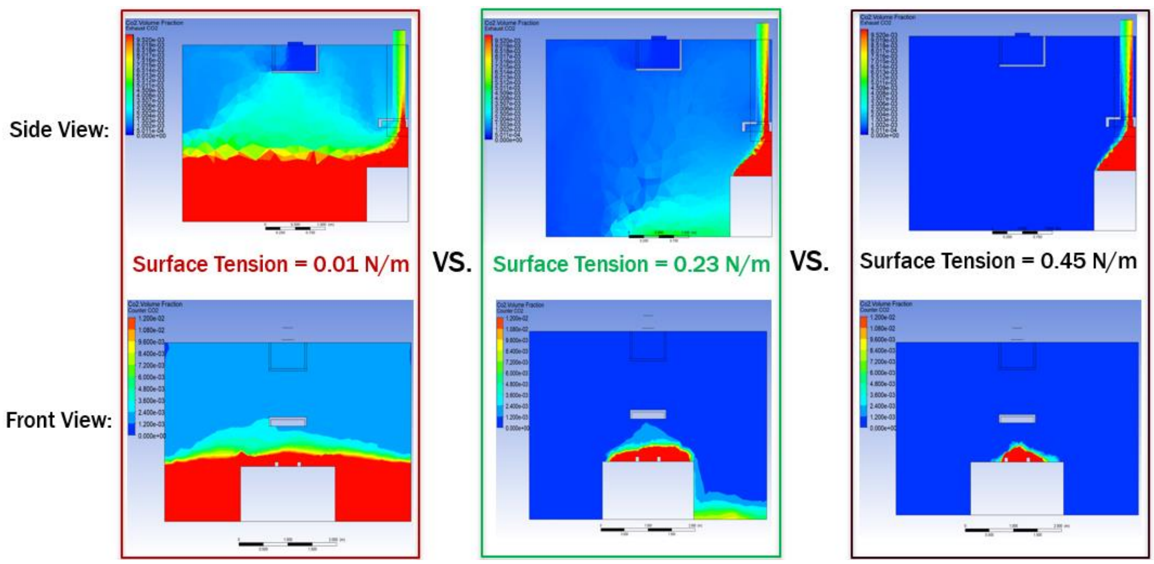


Figure 66: CO2 distribution for various surface tension values using 0.32in. emitter plates

Therefore, it was concluded that this refined CFD model for CE was capable of providing accurate results for the CE measured experimentally. Additionally, the total run time for the simulation is approximately 50 minutes, which is much less than the 3-5 hours that it would typically take to run an experimental CE test.

Summary

In summary, a computational fluid dynamics (CFD) model was generated using Fluent CFD software was shown to be capable of providing an accurate representation of range hood capture efficiency (CE) determined experimentally in accordance with ASTM-E3087.18. The CFD model described herein involved creating a simplified version of the CE test chamber, which was necessary because of excessing computation time and various errors output by the CFD simulation software when modeling all the details of the CE test chamber. The simplified 3D model of the CE test chamber was created using SolidWorks computer aided design (CAD) software and involved eliminating the curvature of range hood/exhaust duct, removing the filters on the chamber inlet and simplifying the CO_2 emitters to reduce the number of details, thus reducing the number of mesh elements. Simplification of the model was also found to reduce the simulation time from 70+ hours to less than 1 hour. It was found that the emitter size, and thus the CO_2 velocity, had a significant effect on the CE determined using the CFD model. It is recommended that future studies experimentally measure the velocity from the various holes on the CO_2 emitter plates and select an emitter diameter that reflects the average velocity from these holes. Due to time and const constraints, this study did not measure the actual CO_2 velocity from the CO_2 emitter plates. Some other recommended future studies involve investigating the effects of cook-top temperature on the CFD simulated CE by varying the temperature on the simplified CO_2 emitters and also investigating the effects of mounting height on the CFD simulated CE by changing the mounting height depicted in the SolidWorks model. Other future studies should look into integrating various range hood details to see how different geometries and depths/widths influence range hood CE. Specifically, it would be of great value to this dissertation to see how range hood re-circulation vents influence CE. Finally, it would also be valuable to this dissertation to investigate the CO_2 distribution in the horizontal discharge exhaust duct that was designed and built during this dissertation. Specifically, it would be valuable to see how the CO_2 is distributed in the 'CO_2 pocket' described in the previous chapter and whether there is a clear difference between the CO_2 concentration in this 'pocket' verses that in a straight segment of exhaust duct.

CHAPTER IX

CONCLUSIONS

Overview

A test facility was built during this study that is the first test facility built from the ground up following guidelines promulgated by a standard recently implemented, namely ASTM-E3087.18. Capture efficiency (CE) is defined as the fraction of cooking contaminants captured by a rangehood and exhausted to the outdoors, as opposed to the total contaminants emitted from a stovetop. The CE test-facility described herein was used to conduct a series of experiments on the cook-top temperature, range hood mounting height and discharge orientation to observe the influence of these test factors on the measured CE. Additionally, a computational fluid dynamics (CFD) model was developed to verify experimental CE results and to gain insight on the velocity, pressure and CO_2 distribution in the test chamber.

Repeatability and Reproducibility Metrics

The ASTM test method for CE (ASTM-E3087.18) does not specify a procedure for determining the repeatability or variability between tests, where repeatability is defined as the observed/allowable deviation in the CE value for test performed repeat times. During the study described herein, three metrics were developed to quantify the repeatability/reproducibility with the first metric (ΔCE) emphasizing tests performed back-to-back without any changes to the test configuration and the other two (α and β), incorporating a mandatory dismount/remount of the range hood between tests.

Results showed that the repeatability metric (ΔCE) showed a higher range of values than either of the reproducibility metrics (α and β). Thus, it was concluded that dismounting and remounting the range hood, can yield more accurate results for CE as indicated by a narrower range of values for α and β compared to ΔCE for varying heights. It is recommended that future ASHRAE/HVI procedures require the dismount/remount of a range hood in order to provide a more accurate representation of the true CE value. Furthermore, using β to quantify reproducibility always yielded higher values than α. Previous studies on burner placement showed front burners to give a larger range of CE values, and thus ASTM-E3087.18 specifies front burner placement. By that same logic, it is recommended to use β as the primary reproducibility metric for HVI/ASHRAE certification procedures, as β yields a higher range of reproducibility values than α.

Determining Steady-State

An important and necessary part of the study reported herein was an analysis and evaluation of steady state conditions to determine the adequacy of requirements specified by appropriate standards. The test procedure for capture efficiency (CE) put forth by American Society of Testing and Materials (ASTM) requires that ten measurements of CE be taken after beginning the emission of CO_2 into the test chamber and after waiting for the test chamber to undergo four air changes. However, the results described in this study showed that the CE can change significantly after four air changes and in some cases will continue changing until ten air changes. In that regard, a CE test that is concluded at five air changes may yield a significantly different CE than a test concluded at nine air changes. Therefore, to ensure high accuracy and minimize variations between repeat tests, it is recommended that future ASHRAE/HVI certification continuously monitor the CE until a specific CE criterion is attained, rather than a chamber-specific criterion, such as four or more air changes. In the studies described in Chapter V – VII, CE measurements were continuously taken until the slope across the ten measurements was less than 0.15%CE (i.e. a steady-state CE was determined as one that does not change by more than 1.5%CE over the course of ten measurements). However, a similar procedure in which the CE is monitored until reaching a specific criterion may also suffice.

Cook-top Temperature

Another important and necessary study of requirements laid out in the current test method for CE, namely ASTM-E3087.18, was cook-top temperature. ASTM-E3087.18 specifies a cook-top surface temperature of 160C when measuring CE values. It should be noted however that the ASTM test method originally specified a cook-top temperature of 200C when it was released in 2017, before being revised to 160C in 2018. Of concern is a lack of clarity as to whether a thorough analysis was performed to investigate how the cook-top temperature influences CE as well as uncertainty, repeatability and variability. The results in this study also showed that although cook-top temperature can have a significant effect on the measured CE, changing it by as much as 9.2%CE, there is in fact little effect on the CE uncertainty, repeatability or variability. Additionally, testing at an even lower temperature of 130C, which is outside previous ASTM ranges, showed that uncertainty, repeatability and variability were unaffected. Therefore, based on this study, it is possible that future certification standards can incorporate a lower cook-top temperature in order to minimize power usage and improve safety.

Mounting Height

The current test method for CE, namely ASTM-E3087.18, does not specify a mounting height. However, the original version released in 2017 specified a minimum mounting height of 0.5m. (19.7in.). Furthermore, previous studies only utilized two mounting heights and since three points are required to draw a curve, there is important need to analyze how the CE is influenced as range hood mounting height changes. Of special concern is that test results have showed that the mounting height can have a significant effect on the measured CE value, changing it by as much 8.2%CE, as well affecting the CE repeatability and variability. With regards to the repeatability and variability, they were found to be minimized at an intermediate mounting height as opposed to either the extreme high/low mounting heights. Furthermore, an intermediate mounting height was found to provide a median value for the CE in 58% of case, as well as an intermediate value for repeatability, reproducibility and variability in many of the cases. It was found that re-circulation vents also contributed to the increased variability between tests. Therefore, it is recommended that future ASHRAE/HVI certification/proficiency procedures utilize an intermediate mounting height and seal off openings for re-circulation vents during certification tests that call for high repeatability.

Discharge Orientation

Previous CE testing, which utilized procedures that follows ASTM-E3087.18, were performed only for vertical discharge orientations. In the study described herein, a CE test chamber was built and modified to accommodate horizontal discharge orientation so that the effects of orientation on CE could be analyzed. Results showed that horizontal and vertical discharges provided comparable measurements for uncertainty; however, the CE as well as its repeatability/variability can vary when changing discharge orientation. Closer observation of the test results showed that the horizontal discharge orientation had a longer segment of exhaust duct and more bends than the vertical discharge, which possibly created CO_2 pockets making it difficult for low speed range hoods to achieve a steady concentration of CO_2 in the exhaust. Therefore, it was concluded that inconsistent exhaust duct design for the vertical and horizontal configuration can lead to increased variations between the two configurations. It is important that future test chamber designs/modifications take proper measures to ensure equivalent duct lengths/bends for both the vertical and horizontal configurations.

Computational Fluid Dynamics (CFD) Analysis

Another important aspect of the research study described herein, is the development of a computational fluid dynamics (CFD) model based on the capture efficiency (CE) test procedure specified in ASTM-E3087.18. In addition to determining the CE in the CFD model using the precise locations specified by ASTM-E3087.18 where CO_2 concentration is measured, the CE was also determined using a volume average of CO_2 in the chamber that considers the CO_2 distribution in the test facility. Results showed that emitter size modeled in the CFD simulation can have a significant effect on the CO_2 distribution and thus measured CE. Additionally, the phase interaction (i.e. surface tension) between Phase 1 (air) and Phase 2 (CO_2) was found to have a significant effect on the CO_2 distribution in the room, with an intermediate value for surface tension based on values found in the open literature giving results for CE that were closest to those observed experimentally.

Summary

Capture efficiency (CE) is defined as the fraction of cooking contaminants captured and exhausted by a range hood, as opposed to those that enter the residence. Understanding of CE is crucial to the efficient design of range hoods as well as human health and safety; however, there is a lack of experimental studies in measuring CE and the factors influencing CE. Although an ASTM testing methodology was recently developed, there are no ASHRAE/HVI test standards or requirements specifying acceptable values of range hood CE. The results of this study, which focus on design and construction of a CE test facility, and evaluating CE test data, will facilitate the understanding of CE while promoting the development of CE requirements/standards.

After completing test facility construction, experiments were performed investigating the influence of different test factors on CE and its repeatability/variability. Results showed that cook-top temperature, mounting height and discharge orientation had a significant effect on CE, but not CE uncertainty. When investigating the effect of these three factors on repeatability/variability, cook-top temperature had no effect on either performance metric, whereas both metrics were worsened when using a horizontal discharge as compared to a vertical discharge. Additionally, an intermediate mounting height improved the repeatability/variability of CE compared to using an extreme low or high mounting height. It was concluded that improper duct design and leakage from re-

circulating vents can worsen the repeatability. Thus, it is recommended that future test standards use an intermediate mounting height, cover re-circulating vents and use a lower cook-top temperature to minimize energy usage in addition to improving safety.

CHAPTER X

SUMMARY AND RECOMMENDED FUTURE STUDIES

Overview

In addition to the recommendations to future ASHRAE/HVI certifications outlined in the previous section, some additional studies are presented in this section that will further aid in the understanding of capture efficiency (CE) as well as assist in the development of future ASHRAE/HVI certifications.

Varying Heights and Testing Different Surface Temperatures.

In the dissertation study described herein, it was found that cook-top temperature did not have much of an influence on capture efficiency (CE) uncertainty or the repeatability/variability of CE, however, temperature was found to have a significant effect on CE. More importantly, when varying the mounting height, it was found that an intermediate mounting height can optimize the results for CE repeatability/variability. Therefore, it is recommended that future studies investigate the cook-top temperature effects at different mounting heights to see if repeatability/variability effects can be optimized even further.

Investigating Effects of Room Size

In the dissertation study on capture efficiency (CE) described herein, it was found that the large test chamber volume led to very length steady state times (i.e. the time required for a stable measurement of CE). The main factor contributing to the lengthy test times is the fact that the test chamber was built with a larger ceiling height to accommodate future testing of island hoods. It is possible that reducing the chamber volume, may lead to reduced CE testing and thus reduced testing costs and CO2 emissions. It is recommended that future studies investigate the chamber size by incorporating a dropdown ceiling or even filling the chamber up with air-tight (or impermeable) boxes to reduce the chamber volume.

Using Multiple CO_2 Sensors

Since it was concluded that continuous monitoring of CE until reaching a certain criterion was found to reduce the variability between tests, it is recommended that future studies investigate the use of multiple CO_2 sensors in order to provide a live feed of CE for continuous monitoring. Currently, the American Society of Testing and Materials (ASTM) requires that all three CO_2 measurements be taken using a single CO_2 sensor. The reason for the single sensor requirement put forth by the ASTM is that the use of a single sensor is meant to minimize the uncertainty in CE since each CO_2 measurement will have the same precision/bias error. Although the use of a single sensor can reduce the uncertainty, it can also cause the data acquisition process to take three times as long as using three sensors, which would allow for measuring the three CO_2 concentrations simultaneously. Therefore, it is recommended that three sensors be integrated and the effects of using multiple sensors on the test time and total CE uncertainty be investigated. Additionally, it is recommended that an additional uncertainty analysis be performed that compares the uncertainty in CO_2 between the two methods (i.e. uncertainty in using one sensor versus the uncertainty when using three sensors).

Additional CFD Analysis

Although the current computational fluid dynamics (CFD) model is capable of providing results for the capture efficiency (CE) that are comparable to experimental results, the CFD model used is highly simplified. It is recommended that future studies integrate more details to the 3D model in hopes of better replicating the experimental test scenario. Additionally, it is recommended that future CFD studies use a velocity for the CO_2 injection rate that matches up to those velocities observed in the experimental test scenario. Furthermore, it is recommended that future CFD studies also investigate the effects of cook-top temperature and mounting height to determine if the simulated results agree with the experimental results.

Tracer Gas Injection Rate

The current ASTM test method for capture efficiency (CE) specifies a tracer gas (CO_2) injection rate that is less than or equal to 0.5% of the range hood air flow rate. Preliminary results show that when decreasing the CO_2 injection rate while holding the airflow rate constant, the value for CE can change by as much as 10%CE. In that regard, two different test facilities may test a specific unit using two different CO2 injection rates that both meet ASTM requirements, which result in significantly different CE values. Therefore, it is recommended that future CE studies fully investigate the effect of tracer gas injection rate on CE and possibly recommend additional test constraints to mitigate any additional discrepancies between CE tests that result from different CO_2 injection rates.

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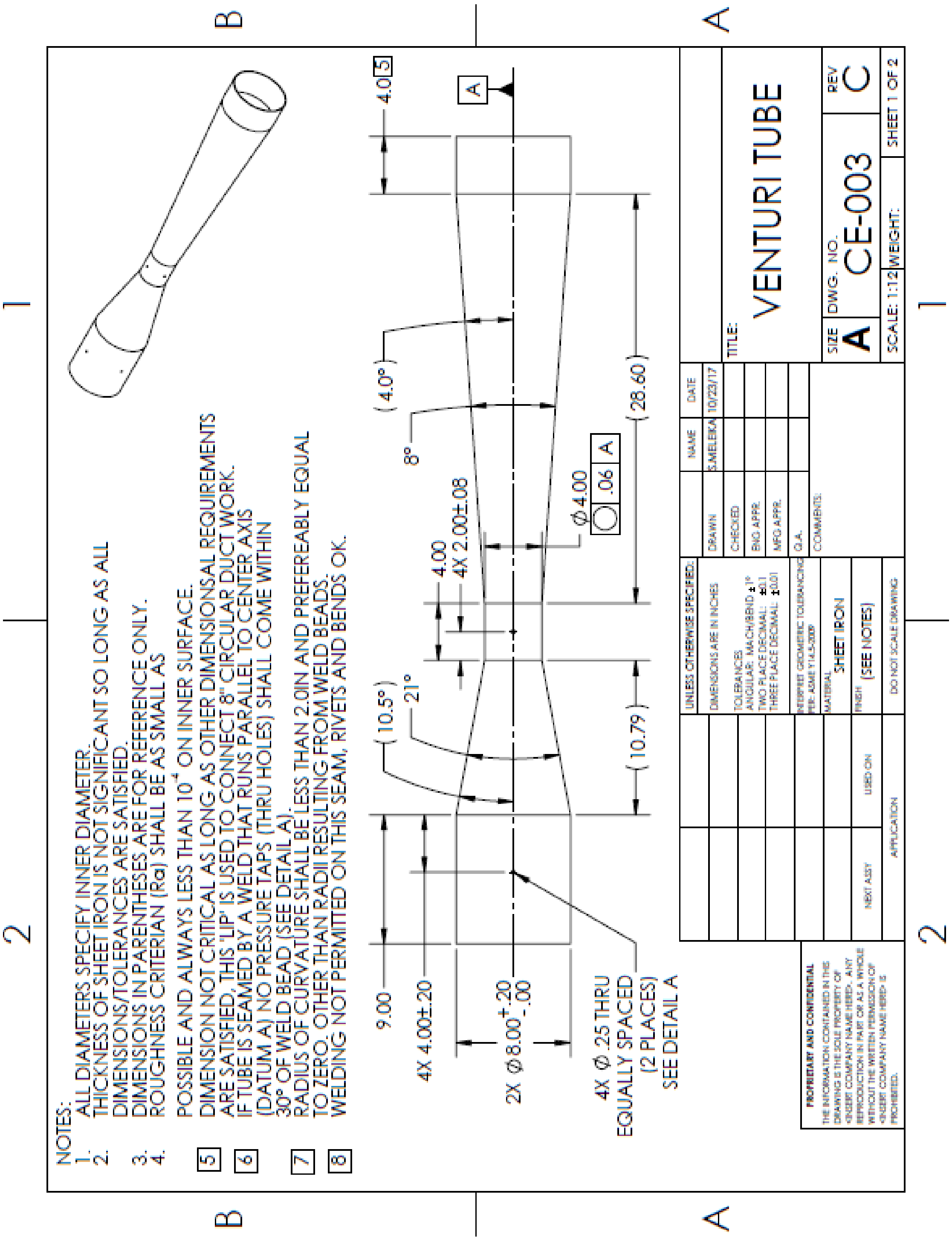
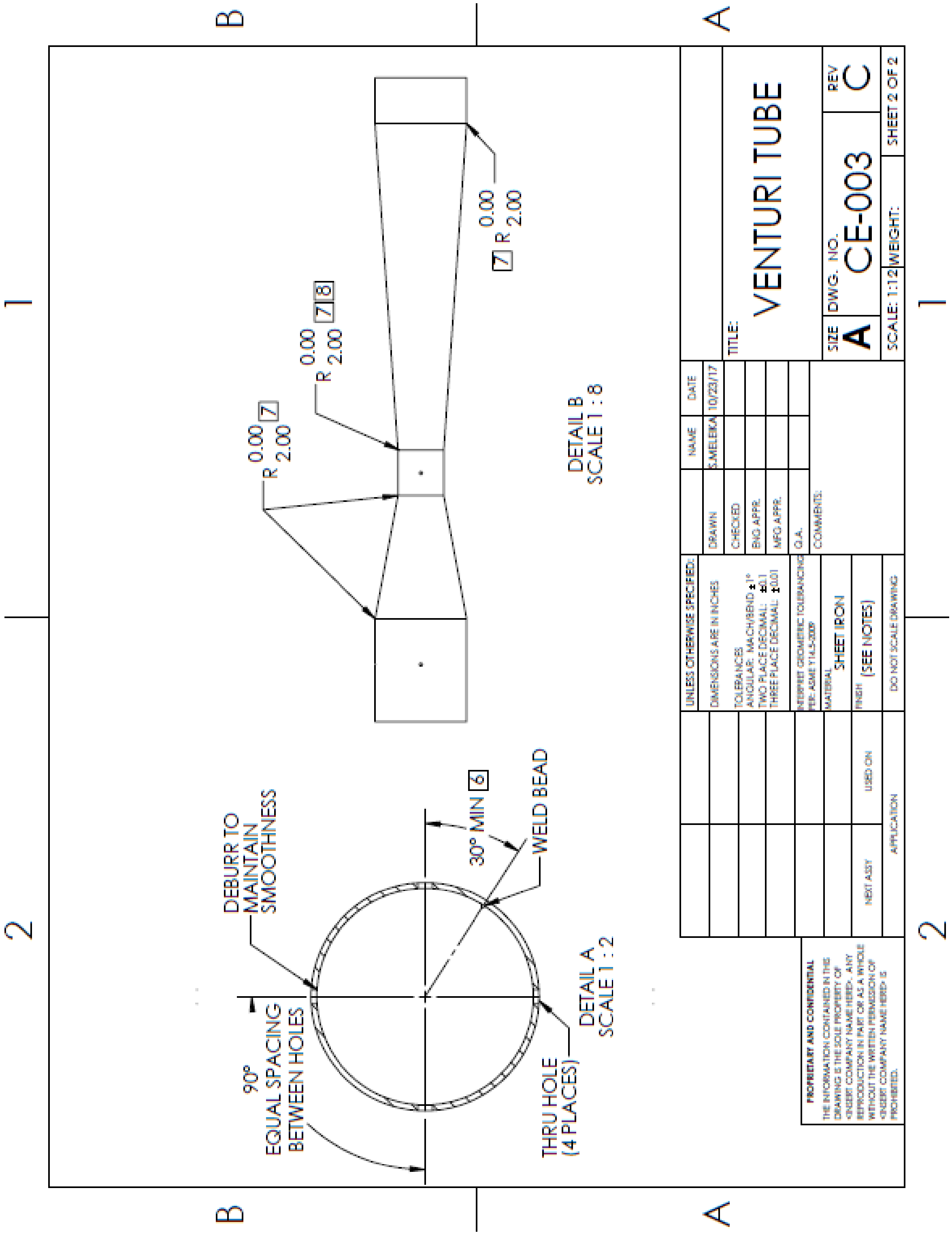
APPENDIX A

DETAILED DRAWING OF VENTURI TUBE

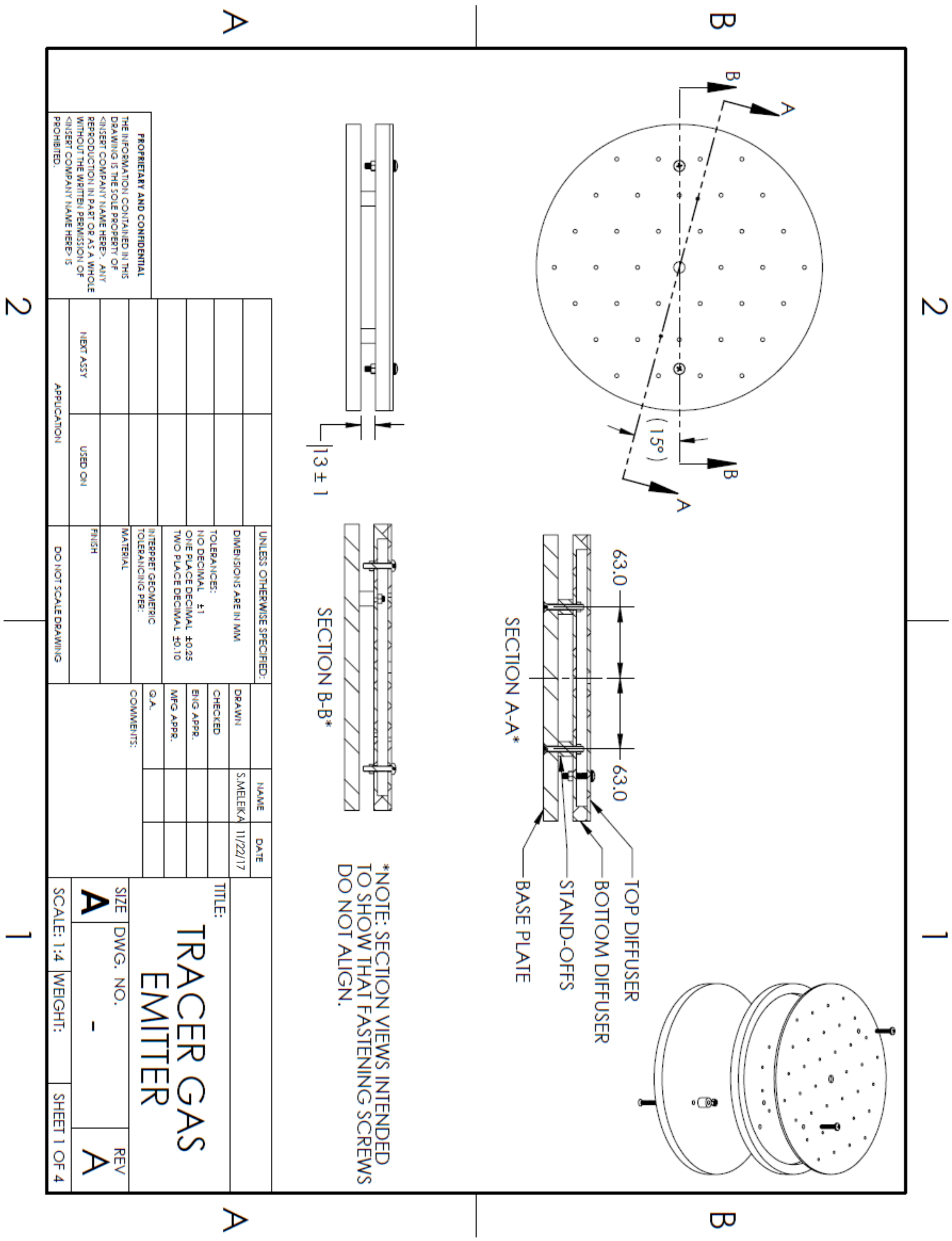


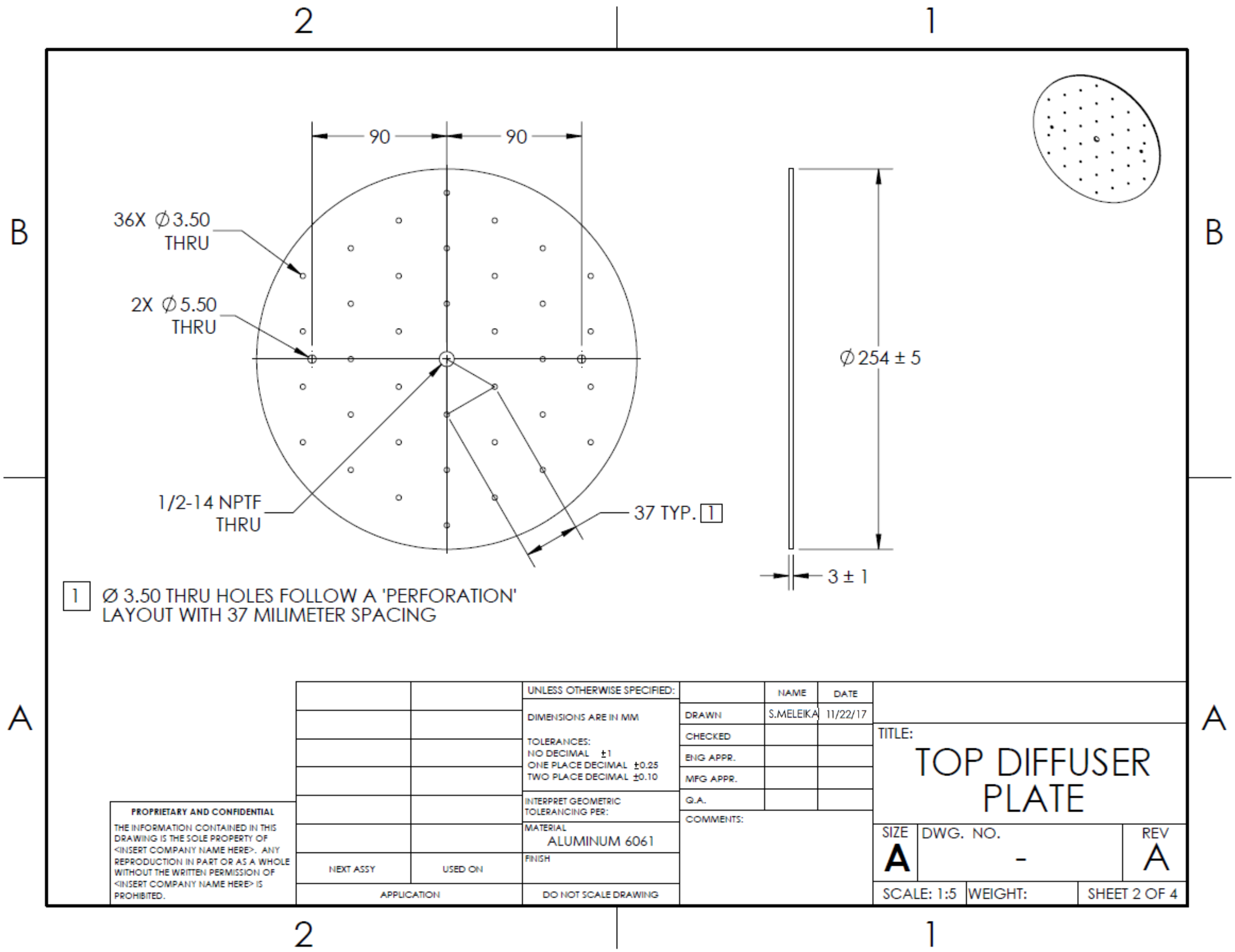


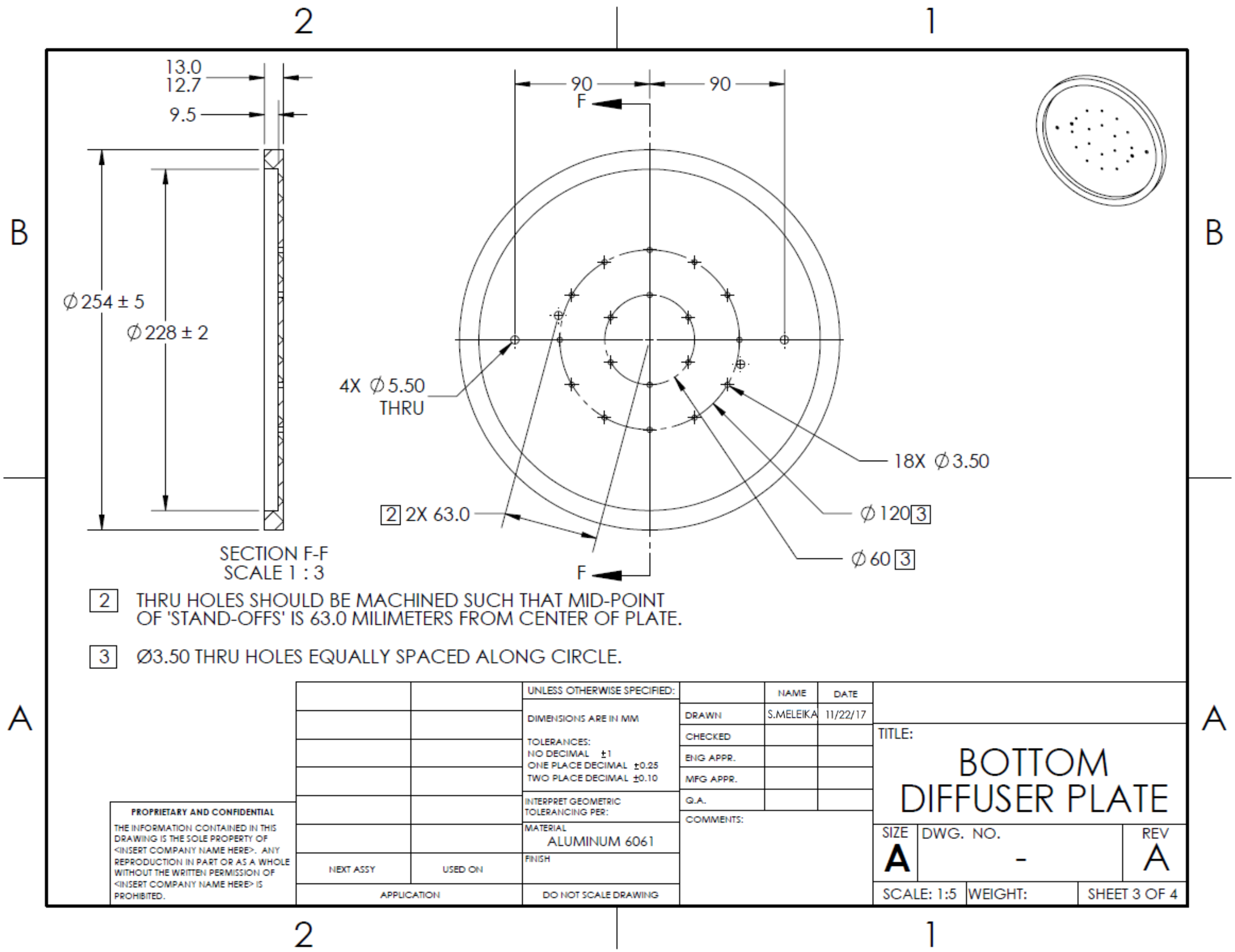
VENTURI TUBE
SIZE A
DWG. NO. CE-003
REV C
SCALE: 1:12
WEIGHT:
SHEET 2 OF 2
DETAIL A
SCALE 1 : 2
DETAIL B
SCALE 1 : 8
DEBURR TO MAINTAIN SMOOTHNESS
90° EQUAL SPACING BETWEEN HOLES
THRU HOLE (4 PLACES)
30° MIN 6
WELD BEAD
R 2.00 0.00 7
R 2.00 0.00 7 8
7 R 2.00 0.00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ANGULAR: MACH/BEND ± 1°
TWO PLACE DECIMAL ±0.1
THREE PLACE DECIMAL ±0.01
INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.5-2009
MATERIAL
SHEET IRON
FINISH
(SEE NOTES)
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
S.MELEIKA
10/23/17
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
TITLE:
A
B
1
2

APPENDIX B

DETAILED DRAWING OF TRACER GAS EMITTERS




90
90
36X ∅3.50 THRU
2X ∅5.50 THRU
1/2-14 NPTF THRU
37 TYP. 1
∅254 ± 5
3 ± 1
1 Ø 3.50 THRU HOLES FOLLOW A 'PERFORATION' LAYOUT WITH 37 MILIMETER SPACING
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
NO DECIMAL ±1
ONE PLACE DECIMAL ±0.25
TWO PLACE DECIMAL ±0.10
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ALUMINUM 6061
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
S.MELEIKA
11/22/17
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
TOP DIFFUSER PLATE
SIZE
A
DWG. NO.
-
REV
A
SCALE: 1:5
WEIGHT:
SHEET 2 OF 4


13.0
12.7
9.5
Ø254 ± 5
Ø228 ± 2
SECTION F-F
SCALE 1 : 3
90
90
F
F
4X Ø5.50
THRU
2 2X 63.0
18X Ø3.50
Ø120 3
Ø60 3
2 THRU HOLES SHOULD BE MACHINED SUCH THAT MID-POINT OF 'STAND-OFFS' IS 63.0 MILIMETERS FROM CENTER OF PLATE.
3 Ø3.50 THRU HOLES EQUALLY SPACED ALONG CIRCLE.
PROPRIETARY AND CONFIDENTIAL
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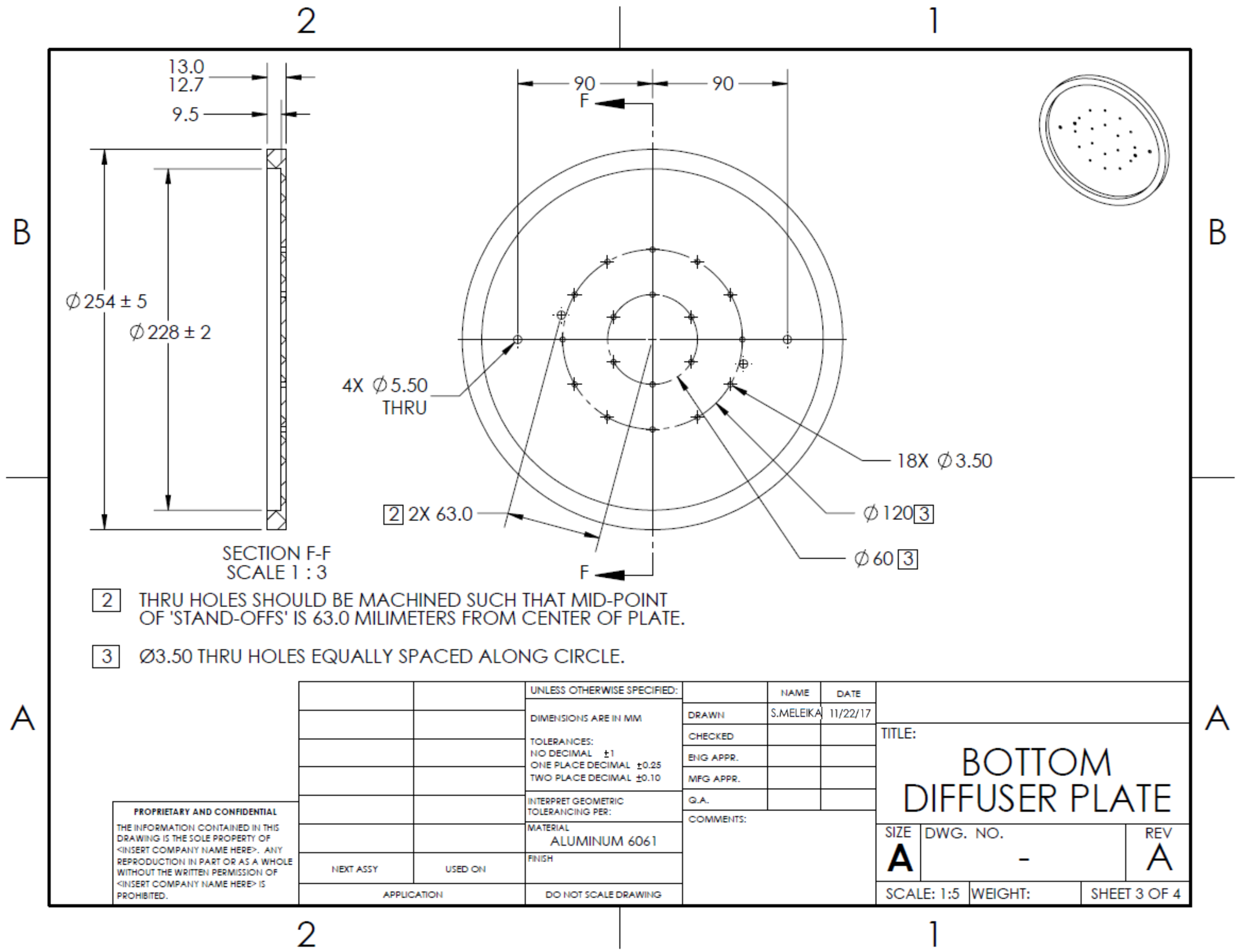
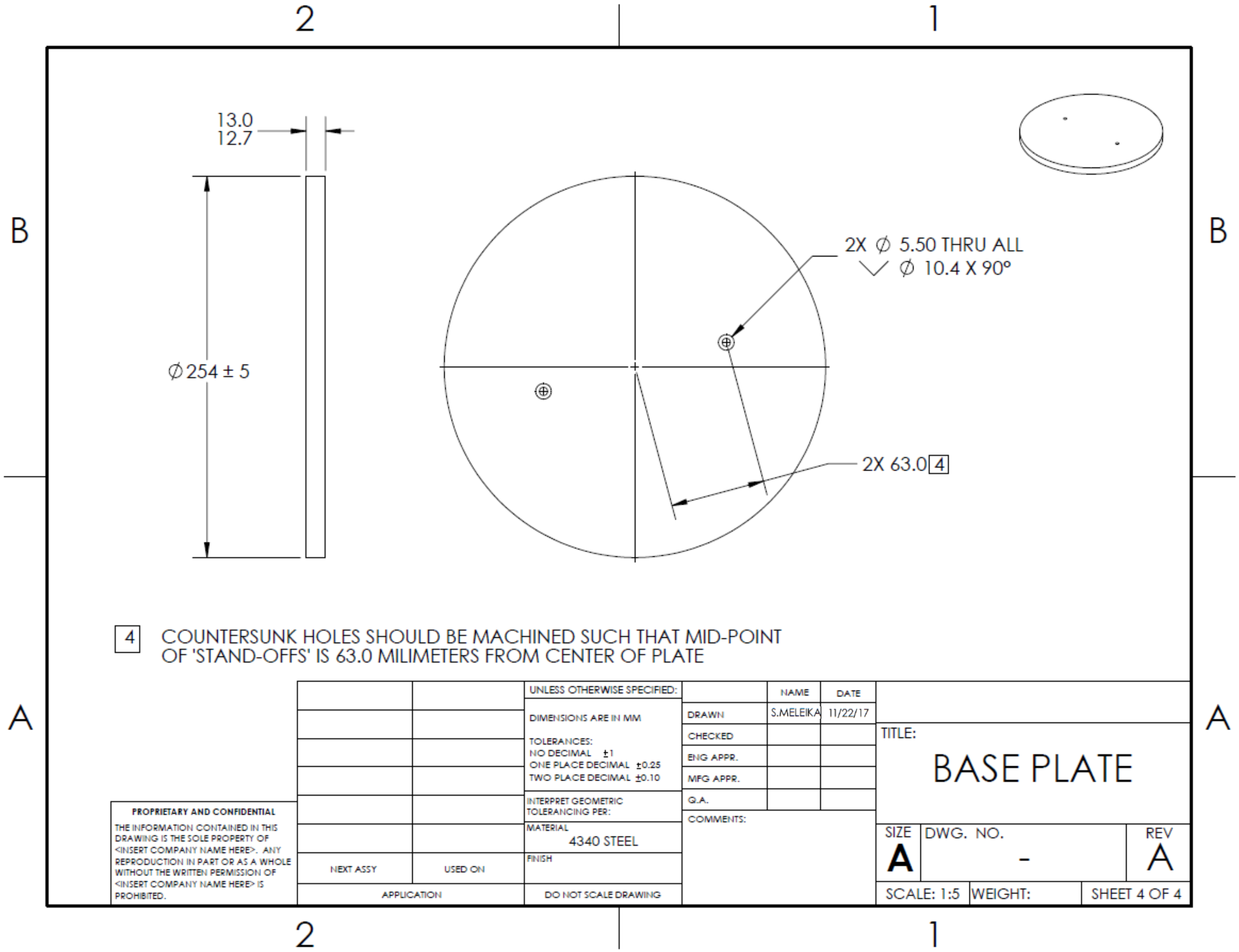
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
NO DECIMAL ±1
ONE PLACE DECIMAL ±0.25
TWO PLACE DECIMAL ±0.10
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ALUMINUM 6061
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
S.MELEIKA
11/22/17
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
BOTTOM DIFFUSER PLATE
SIZE
A
DWG. NO.
-
REV
A
SCALE: 1:5
WEIGHT:
SHEET 3 OF 4
2
1
B
A


13.0
12.7
9.5
Ø254 ± 5
Ø228 ± 2
SECTION F-F
SCALE 1 : 3
90
90
F
F
4X Ø5.50
THRU
2 2X 63.0
18X Ø3.50
Ø120 3
Ø60 3
2 THRU HOLES SHOULD BE MACHINED SUCH THAT MID-POINT OF 'STAND-OFFS' IS 63.0 MILIMETERS FROM CENTER OF PLATE.
3 Ø3.50 THRU HOLES EQUALLY SPACED ALONG CIRCLE.
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
NO DECIMAL ±1
ONE PLACE DECIMAL ±0.25
TWO PLACE DECIMAL ±0.10
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ALUMINUM 6061
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
S.MELEIKA
11/22/17
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
BOTTOM DIFFUSER PLATE
SIZE
A
DWG. NO.
-
REV
A
SCALE: 1:5
WEIGHT:
SHEET 3 OF 4
2
1
B
A



13.0
12.7
Ø254 ± 5
2X Ø 5.50 THRU ALL
⌵ Ø 10.4 X 90°
2X 63.0 4
4 COUNTERSUNK HOLES SHOULD BE MACHINED SUCH THAT MID-POINT OF 'STAND-OFFS' IS 63.0 MILIMETERS FROM CENTER OF PLATE
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
NO DECIMAL ±1
ONE PLACE DECIMAL ±0.25
TWO PLACE DECIMAL ±0.10
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
4340 STEEL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
S.MELEIKA
11/22/17
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
BASE PLATE
SIZE
A
DWG. NO.
-
REV
A
SCALE: 1:5
WEIGHT:
SHEET 4 OF 4

APPENDIX C

PRELIMINARY CE DATA

Test Fan	Test No.	Spd.	Q_ avg. (cfm)	Mt. Ht. (in.)	Aux Fan (%)	CO_2 (L/min)	Rt. Avg. Temp (°C)	Lt. Avg. Temp (°C)	CE (%)	St. Dev (%)	δ (%)	COV (ε) (%)
Fan A	#1	High	87	26	-	12	163	160	66.8	2.31	3.26	8.1%
Fan A	#2	High	89	26	-	12	158	153	64.7	1.28	1.33	
Fan A	#3	High	89	26	-	12	158	153	56.8	1.13	1.34	
Fan A	#4	High	91	26	-	12	158	153	57.7	1.23	1.34	
Fan B	#1	High	224	30	-	28	149	153	90.0	0.78	1.12	2.2%
Fan B	#2	High	196	30	-	28	157	156	86.2	0.60	0.93	
Fan B	#3	High	196	30	-	28	169	171	89.0	0.90	1.03	
Fan B	#4	Low	137	30	60	19	161	170	63.1	0.67	1.30	6.3%
Fan B	#5	Low	137	30	60	19	152	168	69.0	0.92	1.72	
Fan B	#6	Low	117	30	-	19	161	154	63.4	1.21	1.26	N/A
Fan C	#1	Med	168	27	-	23	156	166	88.2	1.13	0.89	2.1%
Fan C	#2	Med	167	27	-	23	145	144	88.1	0.65	1.32	
Fan C	#3	Med	184	27	-	23	144	154	91.3	0.19	0.88	
Fan C	#4	Low	58	27	-	13	163	164	55.8	2.26	1.42	10.2 %
Fan C	#5	Low	69	27	-	13	158	158	64.5	1.37	1.41	
Fan C	#6	High	263	27	-	45	152	156	87.0	1.48	1.95	2.9%
Fan C	#7	High	281	27	-	45	147	159	90.7	1.48	2.88	
Fan D	#1	Low	127	16	-	15	156	162	65.8	1.82	2.13	1.7%
Fan D	#2	Low	124	16	-	15	155	150	68.5	5.18	2.14	
Fan D	#3	Low	124	16	-	15	150	155	66.1	1.21	1.24	

Fan D	#4	Low	124	16	-	15	151	152	65.9	1.45	1.80	
Fan D	#5	Low	134	16	-	15	154	167	66.3	1.13	1.18	
Fan D	#6	Low	127	13.5	-	15	148	163	63.3	1.56	1.74	3.3%
Fan D	#7	Low	126	13.5	-	15	156	163	63.5	1.44	1.24	
Fan D	#8	Low	129	13.5	-	15	147	170	64.1	1.37	1.26	
Fan D	#9	Low	133	13.5	-	15	153	159	59.5	1.38	1.42	
Fan D	#10	High	169	16	-	20	155	160	80.4	0.93	1.12	1.0%
Fan D	#11	High	177	16	-	20	150	164	78.6	1.19	1.44	
Fan D	#12	High	168	16	-	20	151	157	80.2	1.22	1.81	
Fan D	#13	High	167	16	-	20	157	174	79.4	0.63	0.85	
Fan D	#14	High	171	13.5	-	20	147	159	81.5	0.81	1.46	3.1%
Fan D	#15	High	171	13.5	-	20	153	161	84.1	0.64	1.06	
Fan D	#16	High	172	13.5	-	20	154	167	83.3	0.99	1.58	
Fan D	#17	High	171	13.5	-	20	163	170	78.3	1.14	1.45	
Fan E	#1	Low	139	21	65	19	152	163	78.0	0.82	1.49	0.3%
Fan E	#2	Low	140	21	60	19	160	152	77.6	0.84	1.67	
Fan E	#3	Low	137	30	60	19	161	170	63.1	1.09	0.85	6.3%
Fan E	#4	Low	137	30	60	19	152	168	69.0	1.23	1.43	
Fan E	#5	High	215	26	0	28	168	168	76.1	0.96	1.23	N/A
Fan E	#6	High	221	22	0	28	168	153	80.4	1.44	1.59	1.8%
Fan E	#7	High	220	22	0	28	156	157	83.3	1.01	1.40	
Fan E	#8	High	230	22	0	28	151	155	81.8	1.60	2.66	
Fan E	#9	Med	129	22	0	17	153	161	83.9	0.41	0.78	1.1%
Fan E	#10	Med	129	22	0	17	153	158	83.7	0.74	0.84	

Fan E	#11	Med	132	22	0	17	153	166	82.0	0.57	0.96	
Fan E	#12	Med	133	22	0	17	159	165	83.5	0.40	0.73	
Fan E	#13	Med	131	22	0	17	158	166	84.3	0.64	0.90	
Fan E	#14	Med	128	30	0	17	162	174	80.6	0.62	0.86	N/A
Fan F	#1	Low	133	27	41	15	169	158	89.8	0.91	0.84	10.9 %
Fan F	#2	Low	130	27	41	15	160	163	71.8	0.79	1.21	
Fan F	#3	Low	137	27	40	15	158	155	74.9	1.67	1.57	
Fan F	#4	Low	131	27	40	15	163	168	72.5	1.06	1.32	
Fan F	#5	Med	233	27	58	30	170	167	93.8	1.36	1.47	4.6%
Fan F	#6	Med	237	27	61	30	160	158	93.4	2.29	1.34	
Fan F	#7	Med	235	27	65	30	163	168	88.6	0.73	1.98	
Fan F	#8	Med	239	27	64	30	165	157	87.7	1.30	1.38	
Fan F	#9	Med	239	27	58	30	166	158	84.1	0.77	1.89	
Fan F	#10	WS	150	27	52	20	166	153	92.9	0.52	0.87	4.4%
Fan F	#11	WS	154	27	51	20	169	170	75.3	1.15	1.77	
Fan F	#12	WS	152	27	48	20	163	163	76.3	0.73	0.96	
Fan F	#13	WS	153	27	52	20	163	162	70.2	1.17	1.47	
Fan F	#14	High	337	27	82	40	169	150	77.8	2.36	2.52	6.3%
Fan F	#15	High	337	27	82	40	168	150	83.4	0.84	1.98	
Fan F	#16	High	339	27	87	40	157	161	83.3	1.14	2.44	
Fan F	#17	High	328	27	80	40	169	168	89.2	0.60	0.83	
Fan F	#18	High	340	27	82	40	170	154	91.3	0.35	0.95	
Fan G	#1	Low	133	25	46	15	166	164	76.1	1.98	1.72	10.6 %
Fan G	#2	Low	132	25	44	15	154	159	57.2	1.97	1.56	

Fan G	#3	Low	131	25	38	15	166	160	62.1	1.37	1.50	
Fan G	#4	Low	128	25	38	15	154	165	67.0	0.93	1.04	
Fan G	#5	Low	130	25	40	15	158	161	65.8	1.42	0.91	
Fan G	#6	Med	241	25	74	30	153	150	86.4	0.92	1.60	1.7%
Fan G	#7	Med	235	25	66	30	160	160	89.0	0.39	1.37	
Fan G	#8	Med	242	25	65	30	163	160	86.5	0.68	1.36	
Fan G	#9	WS	152	25	53	20	166	167	56.6	2.96	1.89	7.9%
Fan G	#10	WS	149	25	48	20	165	162	67.4	1.14	0.92	
Fan G	#11	WS	150	25	48	20	168	169	66.8	1.61	2.36	
Fan G	#12	WS	150	25	45	20	168	168	62.5	1.54	2.84	
Fan G	#13	High	338	25	94	40	158	150	80.2	0.98	2.00	6.0%
Fan G	#14	High	335	25	84	40	152	152	87.4	0.42	1.34	
Fan G	#15	High	340	25	85	40	162	160	90.2	0.93	1.26	

APPENDIX D

ASTM UNCERTAINTY SAMPLE CALCULATION

The error in individual concentrations is calculated as follows:

$$\delta(C_{Exhaust}) = \sqrt{(\delta_P(C_{Exhaust}))^2 + (\delta_{SE}(C_{Exhaust}))^2}$$
$$\delta(C_{Chamber}) = \sqrt{(\delta_P(C_{Exhaust}))^2 + (\delta_{SE}(C_{Exhaust}))^2}$$
$$\delta(C_{Inlet}) = \sqrt{(\delta_P(C_{Exhaust}))^2 + (\delta_{SE}(C_{Exhaust}))^2}$$

Where, δp = precision error of measurement

δp(C_Inlet) = 0%

δp(C_Exhaust) = 0%

δp(C_Chamber) = 1.25%

The uncertainty in CE is then calculated as follows:

$$\delta CE = CE\left[\sqrt{\frac{(\delta(C_{Exhaust}))^2 + (\delta(C_{Chamber}))^2}{(C_{Exhaust} - C_{Chamber})^2} + \frac{(\delta(C_{Exhaust}))^2 + (\delta(C_{Inlet}))^2}{(C_{Exhaust} - C_{Inlet})^2}}\right]$$

Sample calculation:

$$C_{Exhaust} = 2500ppm, \delta_P(C_{Exhaust}) = 0, \delta_{\mathrm{SE}}(C_{Exhaust}) = 25ppm$$
$$C_{Inlet} = 500ppm, \delta_P(C_{Inlet}) = 0, \delta_{\mathrm{SE}}(C_{Inlet}) = 5ppm$$
$$C_{Chamber} = 1000ppm, \delta_P(C_{Chamber}) = 12.5, \delta_{\mathrm{SE}}(C_{Chamber}) = 2$$
$$CE = \frac{2500 - 1000}{2500 - 500} \times 100\%CE = 75\%CE$$

$$\delta(C_{Exhaust}) = \sqrt{(\delta_P(C_{Exhaust}))^2 + (\delta_{SE}(C_{Exhaust}))^2} = \sqrt{25^2} = 25ppm$$

$$\delta(C_{Chamber}) = \sqrt{(\delta_P(C_{Exhaust}))^2 + (\delta_{SE}(C_{Exhaust}))^2} = \sqrt{12.5^2 + 2^2} = 12.6ppm$$

$$\delta(C_{Inlet}) = \sqrt{(\delta_P(C_{Exhaust}))^2 + (\delta_{SE}(C_{Exhaust}))^2} = \sqrt{5^2} = 5ppm$$

$$\delta CE = CE\left[\sqrt{\frac{\left(\delta(C_{Exhaust})\right)^2 + \left(\delta(C_{Chamber})\right)^2}{(C_{Exhaust} - C_{Chamber})^2} + \frac{\left(\delta(C_{Exhaust})\right)^2 + \left(\delta(C_{Inlet})\right)^2}{(C_{Exhaust} - C_{Inlet})^2}}\right]$$

$$= 75\%CE\left[\sqrt{\frac{(25)^2 + (12.6)^2}{(1500)^2} + \frac{(25)^2 + (5)^2}{(2000)^2}}\right] = 75\%CE[0.023] = 1.7\%CE$$

APPENDIX E

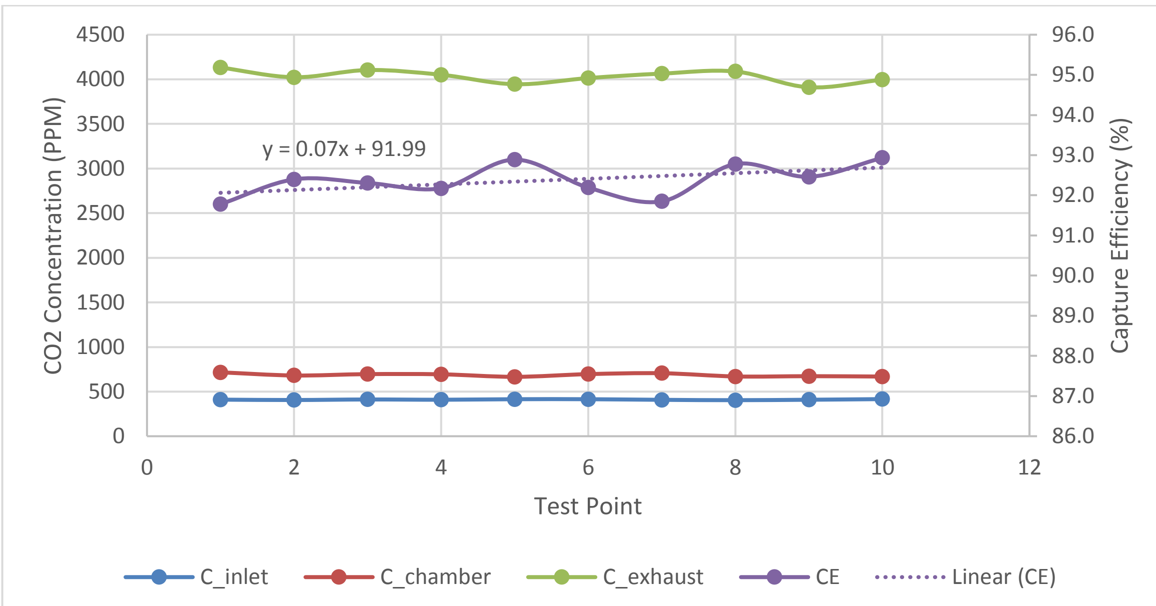
VENTURI TUBE UNCERTAINTY PER ISO5167-4

No.	Condition	Added Uncertainty
1	Diameter ratio (β) between 0.4 – 0.7	None
2	Diameter between 200mm and 1,200mm	None
3	Fabricated using welded sheet iron	1.5%
4	Entry length = 3 duct diameters	0.5%
5	Diameter deviation (circularity) no more than 10% from mean diameter	0.5%
6	Uncertainty in discharge coefficient	1.0%
	Total Uncertainty:	3.5%

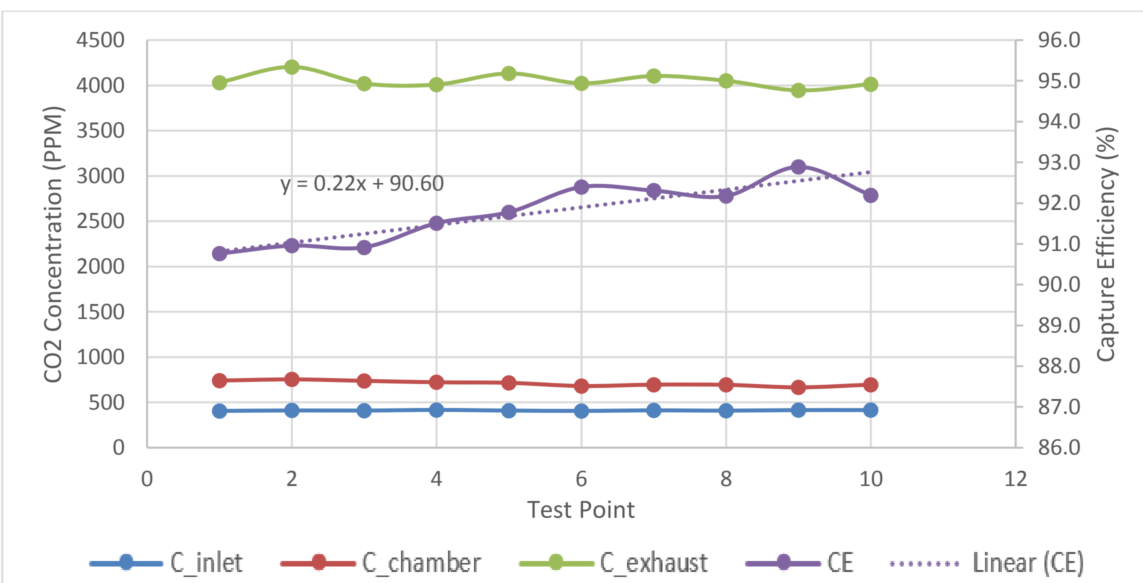
APPENDIX F

PLOT OF TEN CE MEASUREMENTS WITH A SLOPE GREATER (AND LESS) THAN 0.15

Example 1 – Slope = 0.07 (i.e. less than 0.15%CE)



Example 2 – Slope = 0.22 (i.e. greater than 0.15%CE)



Raw data used during test

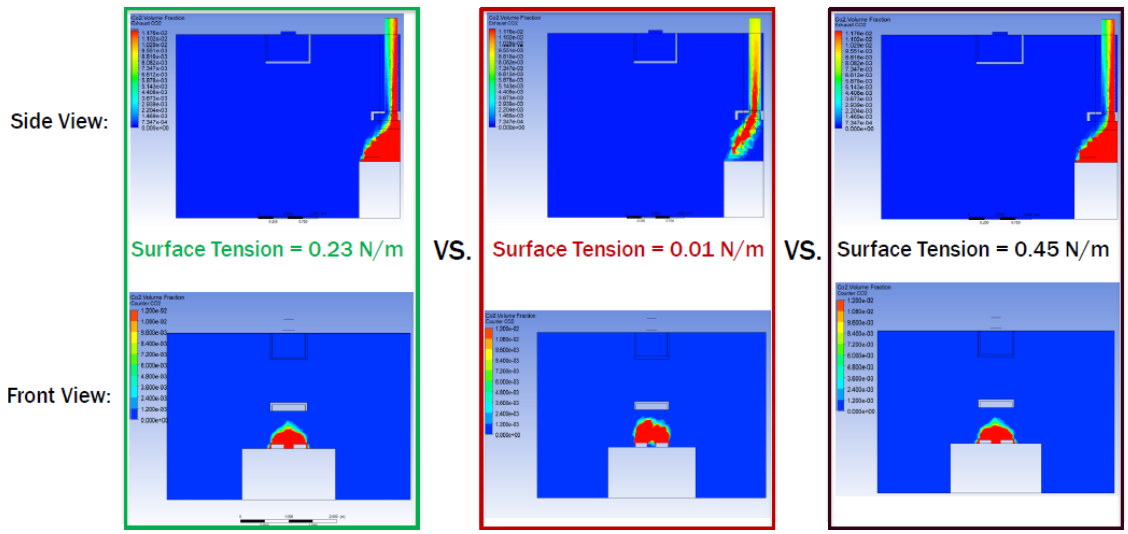
Set No.	C_inlet (ppm)	C_chamber (ppm)	C_exhaust (ppm)	CE (%CE)	Q_hood (cfm)	Right Burner Temp. (°C)	Left Burner Temp. (°C)	Chamber Temp. (°F)
1	406	741	4032	90.76	349	168	170	75
2	411	754	4204	90.96	351	167	168	75
3	410	738	4021	90.92	350	164	166	75
4	417	722	4009	91.51	350	163	164	75
5	410	716	4132	91.78	351	160	162	75
6	406	681	4023	92.40	350	160	161	75
7	412	696	4104	92.31	350	159	160	75
8	409	694	4051	92.17	351	160	160	75
9	415	666	3945	92.89	350	159	161	75
10	415	696	4014	92.19	349	160	160	75
11	408	706	4064	91.85	349	160	160	75
12	404	670	4088	92.78	349	159	160	75
13	409	673	3911	92.46	348	159	159	75
14	416	669	3996	92.93	348	158	160	75

APPENDIX G

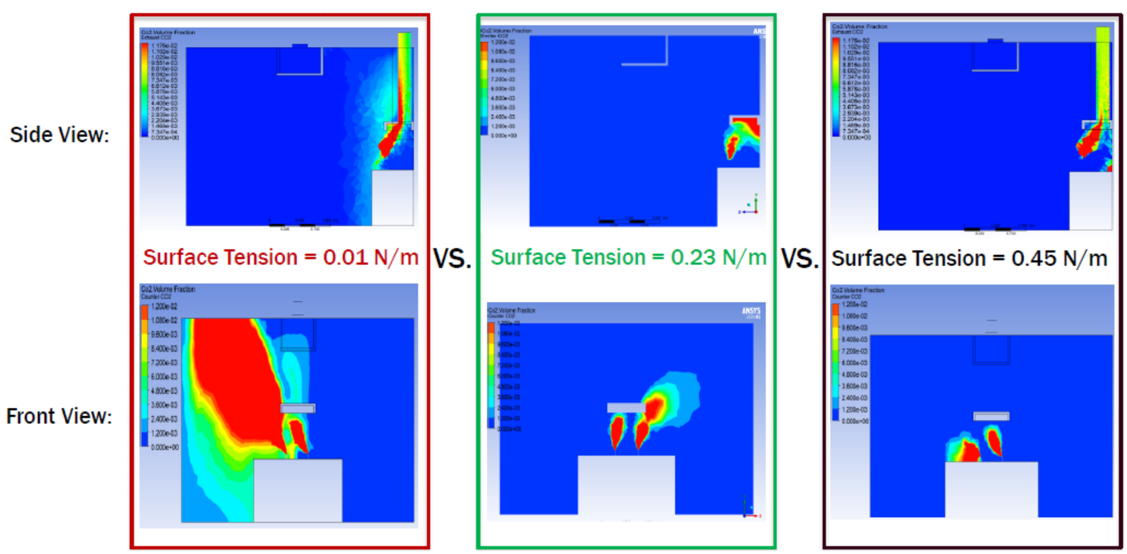
VARYING SURFACE TENSION FOR ALL TRACER-GAS EMITTERS IN

COMPUTATIONAL FLUID DYNAMICS (CFD) MODEL

Results for CO_2 Contour using 10in Diameter Emitters



Results for CO_2 Contour using 0.32in Diameter Emitters



APPENDIX H

CHAMBER AND EXHAUST DUCT LEAKAGE REPORT

Initial Leakage for Chamber and Exhaust Duct – 1/24/2018

DPIS Engineering, LLC
The Builders Solution

Blower Door / Duct Blaster 1511954

1 of 2

Date: 1/24/2018 Plan# Po # Wo # 220560

Builder: James F. Sweeney
Address: 3100 State Highway 47 - Building 6502
Subdivision: Bryan
L/B/S // City Bryan Zip: 77807

Signature:
Inspector: BRIAN COOK

☐ Pass
☑ Fail
☐ NRI
☐ Correct & Proceed
☐ Cancelled w/o Notification

☑ **Re-inspection Required**

Home Start Date: 01/23/2018

Duct Blaster

Is this a reinspection? False Inspection # 1

Supt. Name: **James Sweeney** Phone: **979-575-5182** Called? ☑ Y ☐ N On Site? ☑ Y ☐ N

Inspection Status Summary Meter#: Na

Building Type : **Single Family** Utility Co.: HVAC Contractor:

	NA	Pass	Fail	NRI	Correct & Proceed
Duct Blaster	☐	☐	☑	☐	☐
Blower Door	☐	☑	☐	☐	☐

CFM50 Target	
CFM50 Test	57
BD Location	**Front Door**

Wind Condition ☐ Yes ☑ No

Blower Door Location During Test

Comments:

DPIS Engineering, LLC
The Builder's Solution

Blower Door / Duct Blaster

1511954

Date: 1/24/2018 WO# 220560 Job: PO# Plan#

Builder: James F. Sweeney Home Start Date: 01/23/2018

Address: 3100 State Highway 47 - Buildin

Subdivision: Bryan

City: Bryan State TX Zip:

Lot / Block / Section: //

Duct Blaster

Status

		TDL	Target	LTO	Target
Unit 1		31	5		
Unit 2					
Unit 3					
Unit 4					
Unit 5					

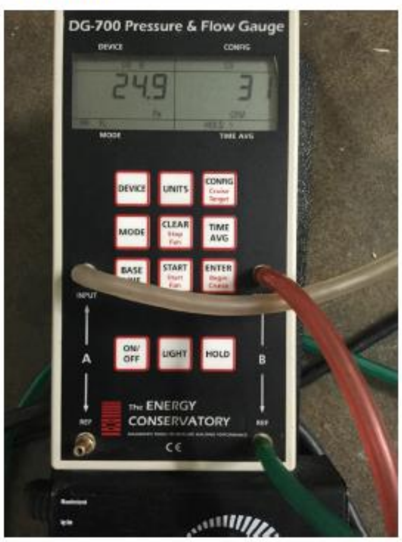
TDL = Total Duct Leakage LTO = Leakage to Outside

Blower Unit Location

Duct Blaster Location During Test Unit

Are all HVAC connections sealed properly? ○ YES ● NO

Comments:



Re-inspection of Exhaust Duct Leakage – 1/25/2018

DPIS Engineering, LLC
The Builders Solution

Blower Door / Duct Blaster 1512699

1 of 3

Date: 1/25/2018 Plan# Po # Wo # 220560

Builder: James F. Sweeney
Address: 3100 State Highway 47 - Building 6502
Subdivision: Bryan
L/B/S // City Bryan Zip: 77807

Signature:
Inspector: BRIAN COOK

- [x] Pass
- [ ] Fail
- [ ] NRI
- [ ] Correct & Proceed
- [ ] Cancelled w/o Notification

Home Start Date: 01/23/2018

Is this a reinspection? True Inspection # 2

Supt. Name: **James Sweeney** Phone: **979-575-5182** Called? ✔ Y ☐ N On Site? ✔ Y ☐ N

Inspection Status Summary Meter#: Na

Building Type : **Single Family** Utility Co.: HVAC Contractor:

	NA	Pass	Fail	NRI	Correct & Proceed
Duct Blaster		✔			
Blower Door	✔				

CFM50 Target
CFM50 Test
BD Location

Wind Condition ☐ Yes ☐ No

Blower Door Location During Test

Comments: **Blower door previously completed**

DPIS Engineering, LLC
The Builder's Solution

Blower Door / Duct Blaster

1512699

Date: 1/25/2018 WO# 220560 Job: PO# Plan#

Builder: James F. Sweeney Home Start Date: 01/23/2018

Address: 3100 State Highway 47 - Buildin

Subdivision: Bryan

City: Bryan State TX Zip:

Lot / Block / Section: //

Duct Blaster

Status Pass

		TDL	Target	LTO	Target
Unit 1		**2.7**	5		
Unit 2					
Unit 3					
Unit 4					
Unit 5					

TDL = Total Duct Leakage LTO = Leakage to Outside

Blower Unit Location

Duct Blaster Location During Test **Interior**

Are all HVAC connections sealed properly? ● YES ○ NO

See Next Page---->>

Comments:

Converted from pascals to cfms, see Ring 4 Flow Table below for results.

Ring 4 Flow Table

Fan Pressure (Pa)	Flow (cfm)	Fan Pressure (Pa)	Flow (cfm)	Fan Pressure (Pa)	Flow (cfm)	Fan Pressure (Pa)	Flow (cfm)	Fan Pressure (Pa)	Flow (cfm)
5	2.4	105	11.0	205	15.4	305	18.8	405	21.7
10	3.4	110	11.3	210	15.6	310	18.9	410	21.8
15	4.1	115	11.5	215	15.8	315	19.1	415	21.9
20	4.8	120	11.8	220	16.0	320	19.3	420	22.1
25	5.4	125	12.0	225	16.1	325	19.4	425	22.2
30	5.9	130	12.3	230	16.3	330	19.6	430	22.3
35	6.3	135	12.5	235	16.5	335	19.7	435	22.5
40	6.8	140	12.7	240	16.7	340	19.8	440	22.6
45	7.2	145	12.9	245	16.8	345	20.0	445	22.7
50	7.6	150	13.2	250	17.0	350	20.1	450	22.8
55	8.0	155	13.4	255	17.2	355	20.3	455	23.0
60	8.3	160	13.6	260	17.3	360	20.4	460	23.1
65	8.7	165	13.8	265	17.5	365	20.6	465	23.2
70	9.0	170	14.0	270	17.7	370	20.7	470	23.4
75	9.3	175	14.2	275	17.8	375	20.8	475	23.5
80	9.6	180	14.4	280	18.0	380	21.0	480	23.6
85	9.9	185	14.6	285	18.2	385	21.1	485	23.7
90	10.2	190	14.8	290	18.3	390	21.3	490	23.8
95	10.5	195	15.0	295	18.5	395	21.4	495	24.0
100	10.7	200	15.2	300	18.6	400	21.5	500	24.1