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RESIDENTIAL INDOOR AIR QUALITY STUDY – ASSESSMENT AND MITIGATION

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RESIDENTIAL INDOOR AIR QUALITY STUDY – ASSESSMENT AND MITIGATION

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Mechanical Engineering
Department of Mechanical Engineering

Nelson Fumo, Ph.D., Committee Chair
College of Engineering

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This is to certify that the Master’s Thesis of

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Abstract

RESIDENTIAL INDOOR AIR QUALITY STUDY – ASSESSMENT AND MITIGATION

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September 2023

An increased awareness in residential indoor air quality (IAQ) has led to an increase in technologies that assist in improving IAQ. Two such technologies include Electro-static (ES) air cleaners and Photocatalytic Oxidizing (PCO) air cleaners. ES air cleaners remove particulate matter from indoor air, but are known to emit ozone, a contaminant, as a by-product. PCO air cleaners abate gaseous pollutants (i.e., Volatile Organic Compounds, VOCs); however, a lack of testing standards creates confusion about their effectiveness in improving IAQ in a real residential home. On the other hand, environmental variables such as temperature and humidity were found to affect VOC sensor readings which complicated the data analysis. In the case of two tested ES air cleaners, the data showed that although the ES air cleaners increased the ozone concentration in the house, the levels are not of concern as they were less than the Food and Drug Administration's (FDA) limit on indoor ozone generation. Regarding two tested PCO air cleaners, minimal indications of an acceleration in VOC abatement were seen. Nevertheless, further insight is given into the methodology behind the real-world testing of PCOs and a correction technique that was used to remove the effect of temperature and humidity on VOC sensor readings.

Keywords: Indoor Air Quality, Ozone, Volatile Organic Compounds, Electro-static Air Cleaner, Photocatalytic Oxidizing Air Cleaner, HVAC

PREFACE

Different portions of this thesis are included in publications, from the author, that have published or will be submitted to an academic journal. Those publications are listed in this section for reference and are included with their publication status at the date of this thesis submission.

- G. Cerrato and N. Fumo, “The By-Product of Ozone from Electrostatic Air Cleaners,” *American Journal of Undergraduate Research*, vol. 20, no. 1, Mar. 2023.
- G. Cerrato and N. Fumo, “Photocatalytic Oxidizing Air Cleaning Technology – A Review” (Manuscript under review)
- G. Cerrato and N. Fumo, “The acceleration of Volatile Organic Compounds by Photocatalytic Oxidizers” (Manuscript under review

CHAPTER 1 – INTRODUCTION

1.1 Overview of Indoor Air Quality

Increased awareness of indoor air quality (IAQ), sparked by the COVID-19 pandemic, has led to an increased interest by manufacturers and the public for technologies that assist in improving IAQ [1]. The Environmental Protection Agency (EPA) defines IAQ as "the air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants [2]." Poor IAQ can lead to a lack of productivity and comfort in addition to negative health effects for indoor residents [3]. The determination of a building's IAQ is dependent on the presence of indoor pollutants which can be measured in concentration levels with the use of IAQ sensors. The primary causes leading to heightened levels of indoor pollution include the collection of indoor sources of air pollutants related to human occupation and the infiltration of outdoor pollution through cracks and openings in a building's envelope. It is reported by the EPA that some air pollutants have indoor concentrations that are two to five times higher than respective outdoor concentrations [4]. The most common indoor pollutants include fine particulate matter (PM), carbon dioxide (CO_2), volatile organic compounds (VOCs), and ozone (O_3). Ozone (O_3) and volatile organic compounds (VOCs) are the contaminants of consideration in this thesis.

1.2 Overview of ozone (O_3)

Ozone is a highly reactive gas, composed of three oxygen atoms. In the Earth's upper atmosphere, referred to as the stratospheric level, ozone is formed through the interaction of solar radiation with molecular oxygen. Stratospheric ozone is essential as it protects the surface of the earth from harmful ultraviolet (UV) radiation from the sun. Tropospheric ozone is harmful because of its proximity to humans at ground or "breathing" level as an air contaminant. The EPA has an air quality index (AQI) related to 8-hour averages of ozone concentrations, in parts per billion (ppb), separated in categories classified as good (0-54 ppb), moderate (55-70 ppb), unhealthy for sensitive groups (71-85 ppb), unhealthy (86-105 ppb), very unhealthy (106-200 ppb), and hazardous (201+ ppb). The EPA also states that a 2-hour average of 600 ppb ozone concentration is considered a significant harmful level with imminent effects [5]. Tropospheric ozone is considered the outdoor ozone that surrounds buildings and structures. Outdoor ozone is found outdoors as a product of sunlight combining nitrogen oxide (NO_x) and VOCs generated from automobiles and coal-fired power plants, in addition to VOCs generated from trees and vegetation. This leads to urban areas having higher levels of outdoor ozone than rural areas where there is less pollution. This is also why outdoor ozone is higher in the daytime and, seasonally, in the summertime where there is more sunlight in comparison to wintertime. Geographical location and meteorological conditions are also factors in outdoor ozone concentrations in terms of the production and transport of outdoor ozone [6].

Indoor ozone concentrations will depend on the introduction of outdoor ozone, indoors, through natural or mechanical ventilation and infiltration through the building envelope. Indoor ozone concentrations will also depend on known indoor sources of ozone by some electrical devices that emit ozone as a by-product, such as electrostatic (ES) air cleaners, photocopiers, laser printers, etc. [7]. FDA standard (21CFR801) sets a limit for devices that emit ozone as a by-product, stating that ozone generation should not exceed 50 ppb (parts per billion). This concentration is related to both the volume of air circulating through the device or an accumulation of ozone in an enclosed living space intended to be occupied by humans. Enclosed spaces include houses, apartments, hospitals, and offices [8].

1.3 Overview of VOCs

VOCs are “organic compounds whose composition makes its plausible for them to evaporate under normal indoor atmospheric conditions of temperature and pressure [9].” The volatility of a VOC depends on its boiling point at standard atmospheric pressure. The lower the boiling point that a VOC has, the more volatile it is classified because it has a greater chance to off-gas from a product or surface in an indoor environment due to it having a higher vapor pressure [9]. For this reason, the World Health Organization places VOCs into three categories: very volatile (VVOCs) due to a lower boiling point, volatile (VOCs), or semi-volatile (SVOCs) due to a higher boiling point [10].

VOCs are found outdoors as a product of vehicle exhaust and burning of fossil fuels, wood, and garbage. VOCs are found indoors as a result of products and materials that contain them, such as building materials (paints, varnishes, caulks, adhesives, carpet, vinyl flooring, composite wood products, and upholstery), home and personal care products (air fresheners, cleaning products, and cosmetics), and human activities (smoking, dry cleaning, cooking, and wood-burning fireplaces) [11]. According to the EPA, the concentration of most VOCs is up to ten times higher indoors than outdoors [12]. In terms of the composition of VOCs in a residential environment, a paper from the Royal Society of Chemistry presents the variability of the different VOCs seen indoor in addition to their respective concentrations indoors. A lot of VOCs correlate with each other, with some VOCs being closely linked to one another in terms of abundance and variability. This means that the presence of a particular VOC may indicate the presence of another. This is the result of a lot of VOCs are mixed together in solvents such as paint or glues, which would explain the previous concept [13].

1.4 Overview of IAQ mitigation

There are many different technologies that have been developed to reduce the concentrations of pollutants indoors including ventilation strategies, the use of high efficiency filters, and air cleaners/air purifiers. The recommendation of high efficiency filters has become more common in HVAC design guidelines with ASHRAE recommending MERV-13 (or higher) filters in order to reduce the transmission of indoor viruses [1]. However, the use of high efficiency filters leads to increases in air resistance which increases the energy consumption of an HVAC system. The use of ventilation works to address IAQ concerns by diluting pollutant concentrations indoors with cleaner outdoor air . Different ventilation strategies are based on different demand factors such as occupancy, floor size, or actual indoor pollutant levels. When ventilation is limited due to harsh weather conditions or when outdoor air is highly polluted, air cleaners or purifiers can be used. Air cleaners can be sold as portable air cleaners placed in singular locations or can be installed in-duct, working to clean the air in all rooms integrated in the HVAC system. In-duct air cleaners can be installed on the supply side of the air handling unit (AHU) or upstream of the AHU on the return side. In-duct air cleaners work in tandem with the indoor blower and will only purify the air when the blower is powered on.

1.5 Overview of electro-static and photocatalytic oxidizing air purifiers

Two common air cleaners include electrostatic (ES) air cleaners and photocatalytic oxidizer (PCO) air cleaners. ES air cleaners work to reduce PM in an indoor environment by charging dust particles in the air that will be captured by oppositely charged plates. The utilization of high voltages in electrostatic air cleaners to create ionized fields can result in the inadvertent or intentional production of ozone [14]. Air cleaners that intentionally generate ozone are identified as “ozone generators”. Producers of such devices erroneously classify ozone as 'activated' or 'energized' oxygen, creating the impression that ozone is a beneficial type of oxygen. The claim made is that the ozone produced from these devices is able to purify the air by removing airborne particles, chemicals, mold, viruses, bacteria, and odors. However, ozone is only moderately effective at cleaning the air at concentrations that are considered unsafe for human exposure. In the case of ES air cleaners that unintentionally produce ozone, they are known do so at much lower levels than ozone generators [14].

PCOs are designed to accelerate the abatement of gaseous, VOC pollutants by way of chemical reactions between a catalyst (usually titanium dioxide) that absorbs gaseous pollutants and a series of UV lights that allow the reactions to take place. The pollutants are either removed or converted into less harmful byproducts such as carbon dioxide and water. The chemical process of reducing VOCs is complex. Some indoor VOCs treated by the PCO air cleaner will not be removed as efficiently as others. In other words, certain PCO air cleaners will react differently with different VOCs [15]. Also, the use of PCO air cleaners can lead to the potential formation of harmful by-products. For this reason PCO air cleaners can be used in tandem with adsorptive filters (i.e. carbon filters) that adsorb gaseous pollutants in addition to filters that contain PCO properties [16] [17] [18] [19]. The EPA’s conclusion on PCOs is that their use in homes is limited because currently available catalysts are “ineffective in destroying gaseous pollutants from indoor air. Some PCO cleaners fail to destroy pollutants completely and instead produce new indoor pollutants [20].”

1.6 Thesis outline and purpose

The purpose of this thesis is to contribute to the assessment of indoor air quality and the mitigation of pollutants in residential applications through the examination of two electrostatic (ES) air cleaners and two photocatalytic oxidation (PCO) air cleaners in a real-world application.

The findings from this thesis will lead to the further characterization of the two technologies and their impact on residential IAQ. This will also include assessing the behavior of ozone and VOCs, indoors, to better understand the experimental results. The ES air cleaners were tested to assess their contributions in the increase of indoor ozone levels during their operation and whether they adhered to FDA standards. The PCO air cleaners were tested to assess the extent to which they were able to accelerate the abatement of spikes in indoor VOC concentrations. In terms of the vertical positioning of contaminant measurement, both the ozone and VOC studies were measured at the breathing zone, which is the considered space for human occupancy where the majority of their time is spent indoors. The breathing zone is also defined as, “the area of a room in which occupants breathe as they stand, sit, or lie down” [21]. Measuring pollutants at the breathing zone, as opposed to in-duct measurements, provides a more realistic depiction of occupant exposure and helps prevent overestimation of experimental results.

Additional discoveries from this thesis will support the continued advancement of these technologies through their evaluation in future real-world testing. This will include specifying the design of experimental procedure based on pollutant behavior, the placement of IAQ sensors, and environmental factors affecting VOC sensor readings. A correction model was developed to minimize variations in VOC readings from the sensors that were based on variations in temperature and humidity, not actual changes in VOC concentrations.

Chapter two presents the literature review of ozone, ES air cleaners and their production of ozone, and the evaluation of PCO air cleaners. The ozone review provides insights into the dynamics of indoor and outdoor ozone, enhancing comprehension of the thesis findings that will concentrate on contrasting various baseline levels of indoor and outdoor ozone. The review of ES air cleaners and their production of ozone gives background on the conclusions of previous tests evaluating the technology. Finally, the review on the evaluation of PCO air cleaners narrates through the development of the testing of PCO air cleaners in addition to the identification of relevant design parameters. Chapter three provides the results and discussion of the ozone experiments. Chapter four documents the development of the climatic correction model in reducing variations in sensor VOC readings due to temperature and humidity. Chapter five provides the results and discussion of the VOC experiments. Lastly, Chapter six summarizes the conclusions from the thesis and its relevance to the general theme.

CHAPTER 2 – LITERATURE REVIEW

2.1 Literature of ozone and ES air cleaners

2.1.1 Characterization of the tropospheric boundary layer and outdoor ozone

The earth's surface layer is a part of the tropospheric boundary level (BL) which is the lower-level atmosphere that is affected by the friction and transfer of heat from the earth's surface. The tropospheric BL develops periodically throughout the day. In the morning, sunlight heats the earth's surface creating a transfer of heat into the atmosphere; eroding the stable layer formed overnight through radiational cooling. The new BL combines surface heating and wind turbulence and creates what is known as the mixed layer, reaching its maximum depth in the afternoon. The rapid growth of the mixed layer coincides with the mixture of outdoor pollutants [22]. As the sun sets, and solar radiation decreases, a new stable nocturnal BL is established which leads to the discontinuity of pollutants at this level. However, there is a residual layer at a higher elevation that contains pollutants from the daytime. An example of the diurnal cycle can be found in *Jacob, J. D* [23]**.**

Ozone is produced photochemically by the oxidation of methane, carbon monoxide (CO), and non-methane hydrocarbons (NMHCs) in the presence of nitrogen oxides and sunlight. This process leads to ozone having strong diurnals variations near the earth's surface layer. During the afternoon, mixing ratios of outdoor ozone increase at its highest coinciding with the combined effect of photochemical production and the mixing of ozone rich air masses from the residual BL. At nighttime, mixing ratios of outdoor ozone are at its minimum due to dry deposition and a lack of solar radiation in the shallow nocturnal BL [24]. Dry deposition is when particles are removed from the atmosphere due to gravity [25].

2.1.2 Diurnal and seasonal characteristics of outdoor ozone

The diurnal and seasonal cycle of outdoor ozone can be related to solar radiation as stated in the *Introduction*. This correlation is illustrated by a study that was conducted by the Department of Environmental Sciences at King Abdulaziz University (KAU) which observed the diurnal and seasonal variations in Yanbu, Saudi Arabia. Table 1 shows the minimum and maximum outdoor VOC concentrations seen in a diurnal cycle for four seasons, respectively [26].

Table 1. Maximum and minimum VOC concentrations in a diurnal cycle for four seasons [26]

	Winter	**Spring**	**Summer**	**Autumn**
Maximum VOC concentration (ppb) / Hour of occurrence	28/17.5	39/12.5	36/11.5	32/14.5
Minimum VOC concentration (ppb) / Hour of occurrence	8/8.5	12/7.5	13/7.5	10/7.5

A couple of things can be concluded from Table 1. One is related to the diurnal cycle of outdoor ozone. The minimum concentrations of ozone occurred at early hours (7:30 or 8:30 AM) for every season. The maximum concentrations of ozone occurred at later hours (11:30 AM, 12:30 PM, 2:20 PM, or 5:30 PM) for every season. This is consistent with the characteristics of the diurnal cycle of outdoor ozone, showed to follow the development of the tropospheric BL mentioned in *2.1.1 Characterization of the tropospheric boundary layer and outdoor ozone*. Outdoor ozone from the residual BL is further mixed and created as solar radiation increases throughout the day. Outdoor ozone levels reach their peak at the height of sunlight. As the sun sets, and solar radiation decreases, outdoor ozone concentrations begin to diminish and stabilize into the nocturnal BL. Another conclusion from Table 1 is that outdoor ozone has a seasonal cycle. The highest range of outdoor ozone concentrations is seen in the spring followed by summer, autumn, and is lowest in the winter. A ranking of months which can also be related to the amount of solar radiation seen in those months.

2.1.3 Infiltration of outdoor ozone into an indoor environment

Outdoor ozone can infiltrate a building's envelope in three different ways. Through cracks and openings in the exterior, natural ventilation, and mechanical ventilation. A parameter used for measuring the infiltration of outdoor in an indoor environment is the I/O ratio. The I/O ratio relates the concentration of indoor ozone as a percentage of outdoor ozone concentrations. Each of the three paths of infiltration have different I/O ratios. Differences in I/O ratios between the two types of ventilation are because outdoor ozone will pass through more filtering in mechanical ventilation than natural ventilation. Infiltrations through cracks and exterior opening have the smallest effect in raising the I/O ratio and will depend on the tightness of the building's envelope.

A study called "Study of outdoor ozone penetration into buildings through ventilation and infiltration" observed I/O ratios under the three paths of outdoor ozone infiltration. The study included the summary of a literature review on I/O ratio values seen in 385 houses for the three paths of infiltration. I/O ratios were listed as 0.09, 0.19, and 0.47 for infiltration, mechanical ventilation, and natural ventilation respectively. These values corresponded to median air exchange rates, or air changes per hour (ACH), and surface deposition rates. The study concludes listing the paths of infiltration in order from lowest to highest I/O ratios. This means that natural ventilation led to the biggest infiltration of outdoor ozone indoors, followed by mechanical ventilation, and infiltrations through cracks [27].

Another study investigated, "The impacts of building envelope design on indoor ozone and health exposures in residential houses [28]." Data was recorded in four rooms, from three houses with old construction, with different exterior finishes and levels of tightness. None of the houses had any significant sources of indoor ozone such as photocopiers or printers. The houses were occupied with no restriction on their daily routines, and data was taken over the period of 10 days. The constructions of the four envelopes, with respective I/O ratios, are summarized in Table 2.

Table 2. Construction of envelopes 1, 2, 3, and 4 [28]

Envelope	**Exterior Wall Finish**	**Wall surface area (ft^2)**	**Window Perimeter (ft)**	**Window to Wall Ratio**	**Wall Thickness (in)**	**I/O ratios**
1	Stucco	143	33	0.21	11.0	0.49±0.24
2	Brick	134	33	0.22	16.0	0.52±0.18
3	Brick	176	61	0.30	12.5	0.68±0.19
4	Painted fiber cement siding	79	31	0.95	9.8	0.48±0.2

The factors of the envelopes were statistically analyzed and correlated with indoor ozone concentrations. The study found that the envelope construction variables that played important roles in influencing indoor ozone concentrations were exterior wall finishing and window to wall ratio. Exterior materials can chemically react with outdoor ozone and diffuse ozone before it penetrates indoors. The study reveals mixed effects from the window to wall ratio. The study concluded that the construction variables observed in the study are reasonable predictors of indoor ozone levels.

2.1.4 Generation of ozone from ES air cleaners

In-duct ES air cleaners, installed in HVAC systems, are manufactured to remove a wide range of airborne particles. The standard operating procedure for ES air cleaners consists of three parts which include ionization, collection, and filtering. ES air cleaners first ionize incoming contaminant particles by generating a field of static electricity. The particles are then collected in a series of discharge plates with laminated film envelopes which are separated by a small intermediate distance. The film is a high dielectric material used as an electrical barrier to prevent electric sparks from an electrical discharge [29]. Carbon filters, positioned as the final step in ES air cleaners, are filters that contain granular pieces of carbon. Remaining contaminated particles react chemically with the carbon material and stick to the filter [30]. Thus, preventing the particles from recirculating back into the house. The ionization of the contaminant particles also leads the ionization of oxygen passing through the ES air cleaner. The formation of ozone through ionization can be simplified in a two-step process as seen in Equations 1 and 2 where M is a third stabilizing molecule (M) [31].

$$e + O_2 \xrightarrow{yields} 2O + e \qquad \textit{Equation (1)}$$

$$O + O_2 + M \xrightarrow{yields} O_3 + M \qquad \textit{Equation (2)}$$

There is a literature review paper named “Electrostatic Precipitators as an Indoor Air Cleaner—A Literature Review” which summarized publications on ES air cleaners. The paper summarizes aspects related to ES air cleaner design that led to higher generation rates of ozone, methods of ES air cleaner testing, and results to the extent that in-duct ES air cleaners had in raising indoor ozone levels in a manufactured test house. The extent to which ozone is generated can be related to product design and operating conditions of the ES air cleaner. Some design factors include charging wire diameter and material, geometry of the ES air cleaner, and the applied voltage. With respect to the amount of voltage applied to the charging wires of the ES air cleaners, a higher operating setting, could lead up to a 50% increase in ozone generation as opposed to a lower setting [32]. A poorly designed ES air cleaner could raise indoor ozone levels above the recommended limit of 50 ppb. For this reason, there are standards given by the California Air Resources Board (CARB) and UL (an accredited standards developer) that are used to certify ES air cleaners in terms of ozone generation with approved test methods [33]. The literature review paper mentioned a study that found the use of the two studied ES air cleaners raised indoors ozone levels by 77 and 20 ppb, respectively. The study concluded that the largest influence in ozone production were the brands of poorly designed ES air cleaners that generated more ozone than necessary, requiring a high voltage output to the charging wires [34].

Another study, "Characterization of potential indoor sources of ozone", included the observation of indoor ozone levels in homes with permanently installed ES air cleaners. The study first measured indoor background ozone levels downstream of the air cleaner powered off. A total of eight in-duct ES air cleaners were evaluated. The blower ran continuously. The ES air cleaner was powered on, and downstream ozone was measured. The study decided to measure ozone downstream and near supply registers to measure the maximum possible ozone before dissipating into the house. Two of the measured air cleaners produced ozone. However, these measurable quantities of ozone decayed to non-detectable levels as it passed through the supply ducts. The study concludes by stating that the ozone emission rates of the ES air cleaners would not produce concentrations greater than 10 to 30 ppb above background indoor ozone levels [35].

2.2 Literature of VOCs and PCO air cleaner testing

2.2.1 Overview of experimental procedures used in the testing of PCO air cleaners

The testing of PCOs consists of the operating conditions of the PCO and the environment that it is tested in, as well as the specific VOCs that are included in the testing. This also involves the manner in which those selected VOCs are injected into the test environment. VOCs are usually chosen based on either how common they are in an indoor environment according to a chosen reference or their expected reactivity with the PCO air cleaner. The injection methods for VOCs in respective experiments have been either as an evaporated gas to be mixed with air or via diffusion from a surface or liquid into a closed environment. The methodology used in the testing of PCOs has evolved over time in search of being able to simulate the realistic conditions in which the PCO is to be implemented in.

Zhong et al. [36] narrate through some of these developments while also providing a systematic assessment of the parameters related to the testing of PCOs. The paper includes a direct observation of the effects that relevant parameters have in the effectiveness of VOC removal by PCO through a series of conducted experiments. The testing performed by Zhong et al. [36] is an improvement in PCO testing in search of a methodology and setup that can simulate the realistic operation of PCOs in HVAC systems. According to Zhong et al. [36], this is in comparison to previous evaluations that have been performed on laboratory bench-top setups under idealistic conditions (low volumetric flowrates, fewer injected VOCs, controlled climates, etc.). The disadvantage of the highly controlled setup is the difficulty in simulating the PCO's performance in full-scale operation. Most PCO studies are performed in controlled laboratory setups, while the need is shifting toward more realistic conditions that the PCO will be applied in. Also mentioned were the differences in objectives found in other evaluations. The majority of studies focus on the design of portable PCO air cleaners in closed chamber testing rather than HVAC applications [37] [38] [39].

The setup used by Zhong et al. [36] was a customized test rig which included a plenum attached to a series of four, parallel aluminum ducts. Inside the ducts were four different combinations of UV lights (ozone and nonozone producing UV lights) and catalysts (titanium dioxide coated on carbon cloth and fiberglass filters). Before VOCs were injected, fans were powered on at a specified airflow rate in addition to powering on the PCO UV lamps. Single VOCs were then injected at a rate deemed appropriate until a desired steady-state VOC concentration was reached. Respective tests for singular VOCs at three different steady-state concentrations were run for an approximate 10 hours. It is important to note that between experiments, the catalysts were regenerated by exposure to UV lamps with a running fan for approximately 10 hours, removing residual VOCs in the PCO systems from past experiments. The quantification method used in the study was the single-pass removal efficiency of the injected VOC by the PCO. This is characterized by the concentration of the VOC before and after the PCO air cleaner. The relevant parameters affecting PCO removal effectiveness included the type of VOC compound, the VOC concentration entering the inlet of the PCO, the airflow rate, the light intensity of the UV lights, and relative humidity. A summary of the results of Zhong et al.'s testing can be seen in *2.2.2 Laboratory testing of PCO air cleaners.*

The study by Zhong et al. [36] provides a good overall characterization of a methodology that can be used in the testing of in-duct PCO air cleaners while highlighting key parametric factors regarding PCO effectiveness. A broader spectrum is seen in a literature review of different air cleaning technologies performed by Zhang et al. [40] regarding fan-driven, products. Zhang et al. [40] did not conduct a specific individual study but rather gave an overall summary of a number of studies with general commentary. Zhang et al. [40] continue to affirm the lack of systematic assessments on air cleaning technology, especially ones performed under realistic conditions. This also includes a lack of assessments performed long-term. Zhang et al. [40] identified 21 articles deemed to be "relevant and conclusive" in their findings related to PCOs. The review classified the articles into two categories of testing environments (laboratory and field) and two sub-categories of laboratory testing methods (single-pass and chamber testing). A single-pass test refers to a method where pollutants are injected in a stream that flows through a chamber connected to the inlet of the air cleaners and exits through a chamber connected to the outlet of the air cleaner. The chamber test method refers to when an air cleaner is placed in a sealed chamber with pollutants injected and mixed within the chamber before the air cleaner is powered on. With respect to PCO testing, Zhang et al. [40] recognized 18 articles related to single-pass laboratory testing, three related to chamber laboratory testing, and zero articles related to field testing. Zhang et al. [40] go on to say that most studies used only singular VOC compounds which led to “good results”. However, because indoor air contains multiple VOC compounds, the results given by those studies could be “misleading”. An observation made by Zhang et al. [39] highlighted how the effectiveness of PCO air cleaners drops from single-pass tests to chamber tests which, according to the authors, indicates that “the technology is not ready for practical application.”

New attempts in recent years have been made in scaling up laboratory testing to full-scale pilot experiments. One study performed by Shayegan et al. [41] shows the process of scaling up PCO testing using the same pilot experimental setup as Zhong et al. [36], as both papers were published by Concordia University. The study differs from Zhong et al.’s [36] in the sense that it has three experimental setups which include a bench-scale setup, a pilot-scale setup, and a full-scale setup. The bench-scale setup is a linear duct with the PCO being installed within. Compressed air, mixed with injected VOCs, enters the setup and is then subsequentially exhausted. The pilot setup is a plenum attached to four parallel ducts, each of which had a PCO installed. The full-scale setup is an oval-like structure set to mimic an actual HVAC system including a radial fan, a HEPA filter, a cooling coil, etc. The three experiment setups increase in size from the bench-scale setup to the full-scale setup. In addition, the conditions used in each setup become increasingly more realistic of what would be seen in a residential HVAC home (i.e., higher flow rates). Table 3 specifies certain characteristics of the bench, pilot, and full-scale setups. A summary on the results of Shayegan et al.’s [41] testing can be seen in *2.2.2 Laboratory testing of PCO air cleaners.*

Table 3. Characteristics of the bench, pilot, and full-scale setups [41]

	Units	**Bench-scale**	**Pilot-scale**	**Full-scale**
Dimensions of PCO *(H x L x W)*	in	2.8 x 3.5 x 0.3	12.2 x 12.2 x 0.3	24 x 24 x 0.3
Setup volume	ft^3	0.22	60	353
Number of UVC lamps	#	2	2	4
Dimension of lamps *(L x D)*	in	2.2 x 0.4	7.9 x 0.6	18.6 x 0.8
Average UVC light intensity	$\frac{W}{m^2}$	36	41	34

Overall, it is clear that the majority of studies performed on PCOs have been in laboratory settings while full-scale experiments are less common. With regard to field testing, the testing or simulation of a PCO in a real-home environment is very limited. The tests that come closest include those that are performed in pilot rooms or test rooms set to replicate an office environment. One European study, conducted by Costarramone et al. [42], included a PCO study with a nonlaboratory chamber test that simulated real life room conditions. The chamber room had air supplied and extracted from it, with VOCs being introduced through the off gassing of a wooden OSB floor and OSB wood panels laid against the room walls. A summary of the results of Costarramone et al.'s [42] testing can be seen in *2.2.3 Field testing of PCO air cleaners.* Another study, conducted by Kolarik et al. [43], reviewed the effect that a PCO air cleaner had on perceived air quality in ventilated test rooms. The VOCs injected in the test rooms were emissions from building materials, old ventilation filters, old computer monitors, and human occupation (5 males and 2 females) as a source of human bio effluents. The study differs from most as it evaluated the performance of the PCO in a qualitative manner (according to 34 male and 16 female human subjects) based on odor intensity, air freshness (stuffy or fresh), and air dryness (humid or dry).

These studies are one of the few that approach the real-life application of a PCO air cleaner in a residential house.

2.2.2 Laboratory testing of PCO air cleaners

The experimental results from Zhong et al. [36] revealed a couple of relevant factors in testing in-duct PCOs. The first was the effectiveness of PCOs on different VOC types. The single-pass efficiency for the PCO air cleaners was the highest in the following order of VOC types: alcohols, ketones, aromatics, and alkanes. Single-pass efficiencies specifically for a set of individual VOCs (injected at an initial concentration of 500 ppb) are reported in Table 4. The values are split into three categories of different combinations of PCO UV lights and filters listed as FGF+UVC, FGF+VUV, and CCF+VUV. The two filters included a fiber-glass filter (FGF) and a carbon cloth filter (CCF). The two types of UV lights included ultraviolet (UV) and vacuum ultraviolet (VUV) lamps.

Table 4. Removal efficiencies for bench & pilot scale setup [36]

	Single-pass removal efficiency (%)		
VOC	**FGF+UVC**	**FGF+VUV**	**CCF+VUV**
Ethanol	22.5	26	34
1-butanol	9	17.5	40
Hexane	3	13	13.5
Octane	4	13.5	15
Acetone	21	21.5	25
MEK	9.5	12.5	28
Toluene	13	17	19
p-Xylene	5	13.25	22

The effectiveness of the PCO varies noticeably for different VOCs for a respective PCO. The study highlights the relationship between the intermolecular forces of a specific VOC and the adsorptive ability of the PCO catalyst or filter. Zhong et al. [36] state that, "the present intermolecular forces are one of the key factors in photocatalytic activity", a point of which can been in the different combination of PCOs. For example, with 1-butanol, the single-pass removal efficiency increases drastically from combination to combination. This is all to affirm that the PCO air cleaner will react differently with different VOCs and that it is the purpose for the development of new catalysts that will react well with a broader range of VOCs. Moving on from Table 3, the second relevant factor taken from the study was the effect that the initial VOC concentration had in the PCO's effectiveness. Focusing on the FGF+UVC PCO, the majority of single-pass removal efficiencies fell for the VOCs as the initial VOC concentrations increased. The observed initial concentrations were 250, 500, and 1000 ppb. The study interprets the behavior as a result of the limited adsorption capacity of the PCO catalyst's surface due to a limited number of fixed active sites. Zhong et al. [36] go on to state that the rate of participating molecules in the PCO reaction is not boosted equally with a noticeable increase in VOC concentration. The third relevant factor was airflow rate. The study reported a gradual decrease in conversion efficiency with an increase in airflow rate. The flowrates observed ranged from 0 to 300 cubic meters per hour (0-177 CFM). An increase in flowrate decreases the residence time, which is the time that VOCs have to be absorbed on the catalyst's surface, therefore giving VOCs less of a chance to be oxidized. The fourth relevant factor was the intensity of irradiance from the UV lights measured in units of energy per area. A gradual increase in VOC conversion efficiency was seen with an increase in irradiance intensity. The final relevant factor, with regard to the UVC PCO, was the effect of humidity on the PCO reaction. In a range of relative humidity (RH) values observed, ranging from 0 to 60% RH, gradual decreases in single-pass removal efficiency were seen with an increase in relative humidity. The study attributes this to the contest between the VOC particles and water molecules for adsorption on the catalyst surface. In other words, humidity in the air acts as a disrupter in the PCO reaction of

VOCs. The study also observed the formation of by-products during PCO operation. Zhong et al. [36] go on to state that by-product formation had a close relationship with the PCO's reaction of different VOCs.

The study performed by Shayegan et al. [41] goes even further in showing the development of more realistic testing to demonstrate the effectiveness of PCO air cleaners. Shayegan et al. [41] compare the different setups in a specific section and do so by keeping the airflow velocity constant. The bench-scale setup is compared to the full-scale at 1.25 m/s (4.1 ft/s), while the pilot-scale setup is compared to the bench-scale setup at 0.5 m/s (1.6 ft/s). The VOCs chosen were toluene and isobutanol at initial concentrations of 100 and 1,000 ppb. Table 5 and Table 6 show the approximate results for the UVC PCO in the bench & pilot scale setups and bench & full-scale setups, respectively.

Table 5. Removal efficiencies for bench & pilot scale setup [41]

	Removal efficiency (%) at 4.1 ft/s of air flowrate			
	Bench		**Pilot**	
VOC	**100 ppb**	**1,000 ppb**	**100 ppb**	**1,000 ppb**
Toluene	16	7.6	7.8	6.6
Isobutanol	70	44	56	25

Table 6. Removal efficiencies for bench & full-scale setup [41]

	Removal efficiency (%) at 1.6 ft/s of air flowrate			
	Bench		**Full**	
VOC	**100 ppb**	**1,000 ppb**	**100 ppb**	**1,000 ppb**
Toluene	11	3	0	0
Isobutanol	55	26	24	8

A lot of trends seen in comparing the different scaled experiments are related to the relevant factors of PCO testing discussed by Zhong et al. [36]. In setups comparing two concentrations of the same VOC, the removal efficiency drops due to the limited adsorption capacity of the PCO. When comparing the bench setup at different airflow velocities and the pilot and full-scales setups (operating at different velocities), the reduction in removal efficiencies resulting from increases in velocity are due to less resident time of the contaminated air under the UV lights. The size of the system is another factor that is seen when comparing the bench setup to the pilot and full-scale setups working under the same airflow rate. As seen in Table 5 and 6, an increase in size led to a decrease in removal efficiency which can be linked to differences in light distribution, most uniform in the bench-scale setup. Lastly, the differences seen in the removal efficiencies of the VOCs are related to the respective reaction of each VOC with the PCO. In short, Shayegan et al. [41] conclude their study by stating that decreases in removal efficiency can be attributed to the size of the system, the inlet VOC concentration, and the air velocity passing through the PCO. Shayegan et al. also stated that “that small-scale results are not sufficiently accurate and reliable for direct extrapolation to large-scale application in the design of the UVC-PCO system.” The authors add that, “further studies are required to evaluate the effect of scaling up for indoor real conditions…”

In Zhang et al.’s [40] literature review, they conclude that PCO air cleaners can reduce the concentrations of some VOCs. However, they can produce harmful by-products too. The authors add that standard conditions and procedures are needed for the evaluation of air cleaner performance. Another literature review was performed by Mata et al. [44] reviewing air cleaning technologies in general. The study focuses on the selection of articles that present technologies that are either ready or close to being applied in indoor environments by consumers. One article presented in the literature review by Mata et al. [44] was by Weon et al. [45] which presented a PCO air cleaner design that was evaluated in a chamber test. The article focused on the improvement of a titanium-dioxide catalyst that is more efficient in the scaled-up application of a PCO. Five VOC gases were injected at a target concentration of 10,000 ppb with each VOC being degraded at different rates, respectively. The article notes that the order of removal efficiency from highest to lowest was formaldehyde, ammonia, acetaldehyde, acetic acid, and toluene, respectively. The study also states that the PCO air cleaner with the specified photocatalyst filter was able to achieve 72.1% average removal efficiency in 30 minutes of operation. Testing protocols were based on a standard by Korea Conformity Laboratories (KCL). The findings from Weon show major promise in the development of a PCO air cleaner to be used in indoor applications with results showing high removal efficiency with high initial concentrations. It is important to note that the article did not mention the specific airflow rate or velocity but rather refers the reader to the KCL standard used. Referring back to the literature review by Mata et al. [44], the group concludes by saying that PCO air cleaners are promising air cleaning technology but there are aspects that need to be considered before their use in indoor air applications. They continue to affirm the factors discussed in this paper (i.e., light intensity, air flowrate, concentration levels, relative humidity, etc.) as the relevant variables in PCO design. By-products continue to be an issue with PCO efficacy.

2.2.3 Field testing of PCO air cleaners

Now, the focus will shift towards highlighting a couple of studies that have been performed in non-laboratory experimental setups and what they have to say about PCO effectiveness. Even though the qualitative-perceived air quality study performed by Kolarik et al. [43] does not present a quantitative evaluation of the PCO in terms of concentration, it is worth mentioning that the application of the PCO in the study was close to a real-life application of a PCO. The conclusions of the study were that human occupants perceived improvements in the air quality of the test rooms polluted by the building materials, used ventilation filters, and old computer monitors, but not of test rooms polluted solely by human emissions (consistent of alcohol VOC compounds). The study attributes an increase in dissatisfaction of perceived air quality to incomplete oxidation of the most common alcohol VOC types emitted off humans, in addition to the creation of by-products from the PCO. The study included a numeric value, called Clean Air Delivery Rate (CADR) which measures the air-cleaning effect of the PCO air cleaner. The computation of CADR is used and explained in *5.6 Evaluation of PCO performance*. The perceived effectiveness expressed as CADR depended on the different types of pollution sources which can be linked to different VOCs, altogether. An observation in *2.2.2 Laboratory testing of PCO air cleaners* related to differences in removal efficiency due to different VOC compounds and types.

The European pilot room study, performed by Costarramone et al. [42], does present the quantitative evaluation of a PCO installed in a non-laboratory setting. The study included four commercial PCO air cleaners bought without adding any modifications. Two pilot rooms were considered, with one being thermoregulated (labeled the BEF platform) and the other not being thermoregulated (labeled the EVALIS platform). The two PCO air cleaners (named E8 and E15) labeled as the most efficient, as per a set of separate laboratory testing, were placed in the BEF pilot room regulated at 77 °F and 60-80 %RH. Tables 7 and 8 show the approximate variations in initial VOC concentration (converted to ppb) seen from the powering on of the E8 (for 2 and 5 days) and E15 (for 3.5 days) PCO air cleaners, respectively. Positive values are representative of percent increases while negative values are representative of percent reductions in VOC concentration.

Table 7. Variations in VOC concentration for the powering on of the E8 PCO [42]

	Initial concentration (ppb)	**Variation of concentration (%)**	
VOC	**0 days**	**2 days**	**5 days**
Formaldehyde	9.8	96	88
Acetaldehyde	8.2	36	58
Acetone	43	-8	4
Toluene	4	-4	-72
Limonene	9.3	-46	-70
Hexanal	26.4	-58	-76
Alpha-pinene	45.2	-50	-62
Beta-pinene	11.1	-56	-70
Pentanal	6.3	-58	-78
1-pentanol	3.3	-56	-80
Octanol	5.45	-60	-82
3-carene	10.4	-54	-70
nonanal	6.5	-60	-80

Table 8. Variations in VOC concentration for the powering on of the E15 PCO [42]

	Initial concentration (ppb)	**Variation of concentration (%)**
VOC	**0 days**	**3.5 days**
Formaldehyde	12.2	20
Acetaldehyde	11.4	-8
Acetone	46	-24
Toluene	2.4	-56
Limonene	11	-78
Hexanal	34.2	-80
Alpha-pinene	55.3	-76
Beta-pinene	12.4	-78
Pentanal	7.7	-80
1-pentanol	5	-88
Octanol	7.5	-72
3-carene	11.9	-76
nonanal	8.26	-88

Not shown in the data given in Tables 7 and 8 is that the study reports that the E15 did not release any by-products during its operation while the E8 was shown to generate NO_x as a by-product. The results show a couple of trends regarding the effectiveness of the evaluated PCOs. First, the PCOs were most effective in reducing the heaviest VOCs. On the other hand, the concentrations of Formaldehyde, Acetaldehyde, and Acetone, which are considered light VOCs, showed minimal changes or even increased. Also noticeable was the rate at which the concentration dropped. As seen in Table 6, certain VOCs reached higher percentages of VOC reduction at 2 days than other VOCs. Toluene had the slowest reduction as its percent reduction was 4% on day 2 before exponentially increasing to 72% in day 5. Overall, the comparison of 2 to 5 days for the E8 PCO air cleaners showed that longer operation led to continual degradation of the VOCs. It is important to note that while the majority of VOCs experienced reductions in concentrations, the initial concentrations were low in magnitude, which bodes well for the PCO's performance. Also not seen in the tables was information the study gave on the aging of the PCO's photocatalyst. The study mentions that in a long-term testing of the PCO, the quantitative clean air delivery rate (CADR) reached a high after a month, remaining stable after two months. CADR decreases at a faster pace after the duration of 4 months. The study attributes this to an aging in the output of the UV lamps and saturation of the photocatalytic media. The results of Costarramone et al.'s [42] testing give valuable insight in the testing of PCO air cleaners under conditions close to real-world applications.

As stated in the section *2.2.1 Overview of experimental procedures used in the testing of PCO air cleaners*, the testing of PCO air cleaners in the field is extremely limited. This may be due to the factors discussed in the section *2.2.2 Laboratory testing of PCO air cleaners*. Since the laboratory testing of PCO air cleaners has resulted in mixed results, the focus of PCO research has been on the development of new photocatalysts that are better suited to be tested in scaled-up, realistic environments.

CHAPTER 3 – METHODOLOGY AND RESULTS FOR THE EVALUATION OF OZONE PRODUCTION FROM TESTED ELECTRO-STATIC AIR CLEANERS

3.1 Testing facilities for ozone experiments

The ozone experiments were conducted at the two test and research houses at the University of Texas at Tyler. The test houses are identical in size and layout with an area schedule of 1,470 square feet (excluding the garage, covered porch, and covered patio). The houses have an interior volume of 11,939 cubic feet and are shown in Figure 1. Test house #2 (on the left) has a tight building envelope (representative of new construction methods) while test house #1 (on the right) is draftier (representative of older construction). Both test houses have infiltration ratings quantified as air changes per hour ACH at 50 pascals (ACH50) from a blower door test reported in the air leakage reports of the houses. Test house #1 and #2 have ACH50 ratings of 4.47 and 1.87, respectively.

They both have a brick exterior finish with a total of nine windows for each house. The houses each consist of 3 bedrooms, 1.5 bathrooms, and an open concept area which includes the living room, dining room area, and kitchen. Neither test houses have regular occupants, nor are they furnished.

Figure 1. Test houses at the University of Texas at Tyler

3.2 Ozone monitoring

The model 202 ozone monitor from 2B Technologies was used to monitor ozone in the living room. The ozone monitor was zeroed out for every experiment (see *Appendix A*). Readings from the ozone monitor have an uncertainty of ±1 ppb or 2% of the reading. Since all readings inside the house are below 50 ppb, the uncertainty associate of readings inside the house is 1 ppb. The ozone monitor was stationed inside the test house and placed in two different positions throughout all the ozone experiments. For ozone experiments 1 through 4, the ozone monitor was placed on a stool underneath the supply registers as illustrated in Figure 2. In ozone experiment 5, the ozone monitor was placed on a ladder about an inch and a half from the ceiling close to the supply registers as illustrated in Figure 3. The location of the stool setup was determined as the result of a stratification test and a test that measured the critical point of ozone in the test house (*see Appendix B*). Outdoor ozone data was received from the environmental monitoring station in Tyler, Texas, recorded in the Texas Commission on Environmental Quality (TCEQ) database [46]. The uncertainty of the outdoor ozone readings given by the ozone monitoring station have an uncertainty of 0.5 ppb.

Figure 2. Stool setup for the ozone monitor

Figure 3. Ladder setup for the ozone monitor

Figure 4 shows the location of the ozone monitor and the four nearest supply registers with respect to the house layout.

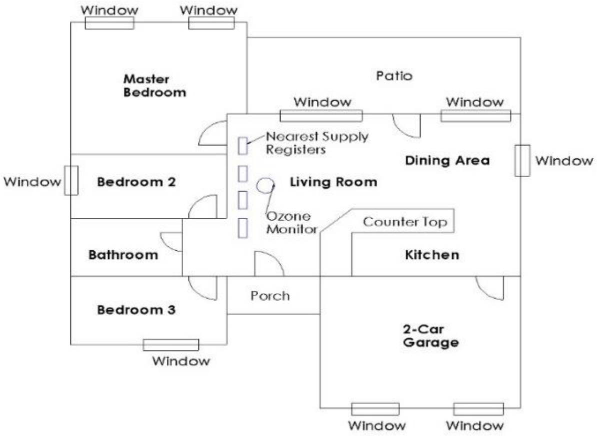


Figure 4. Ozone monitor location and nearest supply registers in house layout

3.3 Overview of ozone experiments

All ozone experiments included the AHU fan being powered on continuously at 100% corresponding to 803 CFM, which was given by the diagnostics portal of the HVAC system. Setting the AHU fan on at 100% allowed for good air mixing within the test house at 4.03 air changes per hour (ACH). Experiment 1 was set to show baseline indoor ozone levels (due to infiltrations only) in house #2. Experiment 2 compared the baseline indoor ozone concentrations of the test and research houses. Experiment 3 highlighted the increase in indoor ozone from experiment 1 due to ventilation, and in experiment 4, the ES air cleaner is powered on. The amount of mechanical ventilation used in ozone experiments 3 and 4 was 6.3% of fresh air intake. This percentage was computed by dividing the flowrate of fresh air introduced into the house (50 CFM) by the supply flowrate (803 CFM). In experiment 5, ventilation was powered off to show the increase in indoor ozone due only to the powering on of an ES air cleaner. Experimental 6 is identical to experiment 5 with the only difference being that indoor ozone concentrations were measured near the supply registers. Experiments 3 through 5 were repeated for both ES air cleaners A and B.

Certain technical details of the ES air cleaners including the dimensions, material, and specific voltage generated from the charging wires are not available publicly as they are not listed in the technical specifications of the air cleaners. A disclaimer of which should be taken into consideration when interpreting the results of the study. There is a documented difference in the operation setting of the ES air cleaners which is the voltage level (maximum, medium, or minimum) applied to their respective charging wires. ES air cleaner A had an actual distinction between “on” and “max-on”, while ES air cleaner B only had an “on” option.

Table 9 summarizes the setup of all six ozone experiments.

Table 9. A summary of the setup for all six ozone experiments

Experiment	**Mechanical ventilation**	**Sensor location**	**House**	**Duration (Days)**
1	Off	On stool in living room	2	1
2	Off		1 and 2	1
3	On		2	ES air cleaner A: 1 ES air cleaner B: 1
4	On			ES air cleaner A: 1 ES air cleaner B: 1
5	Off			ES air cleaner A: 2 ES air cleaner B: 3
6	Off	On ladder in living room		ES air cleaner A: 2 ES air cleaner B: 3

3.4 Results and discussion of ozone experiments

For all plots in the ozone results section, the horizontal green line represents the FDA standard 21CFR801 mentioned in the *introduction* and the vertical red line separates days of data.

3.4.1 Baseline indoor ozone levels in UTT house #2 (Ozone experiment 1)

Figure 5 shows the ozone data for ozone experiment 1 which was performed in test house 2 with the sensor located on a stool in the living room, without mechanical ventilation.

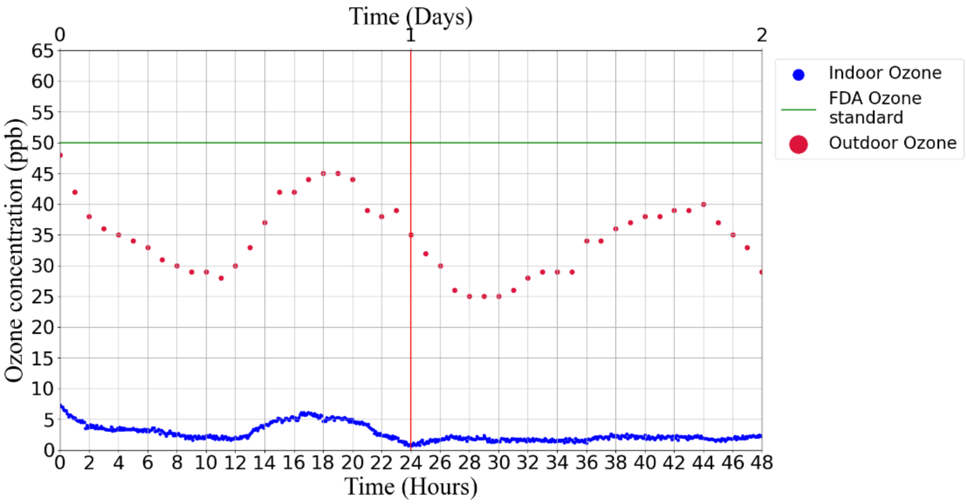


Figure 5. Ozone experiment 1 results for test house #2

Since there is no source of ozone inside the house with the electrostatic filter off, and no ventilation, levels of ozone can only be affected by infiltration. As discussed in *2.1.5 Infiltration of outdoor ozone into an indoors environment*, I/O ratios tend to be affected the least due to infiltrations and will depend on the tightness of the building's envelope. This seems to be the case from the data in Figure 5. The indoor ozone levels are following the outdoor trend at a very low magnitude with a moderate correlation coefficient of $R^2 = 0.47$. This is representative of the fact that house #2 is constructed with a tight envelope. The average baseline concentration of indoor ozone seen in the house was 2.7±1 ppb, corresponding to a I/O ratio of 0.08±0.03, which will be used as a reference for comparison in determining the increase in indoor ozone when the ES air cleaner is powered on.

3.4.2 Comparison of baseline indoor ozone levels in the UTT test houses (Ozone experiment 2)

Ozone experiment 2 was performed in both test houses 1 and 2 with the sensor located on a stool in the living room of each house respectively, without the use of mechanical ventilation. Figure 6 shows the baseline indoor levels of ozone in Test house 1 and 2 for a period of 24 hours where average outdoor ozone concentrations were closest.

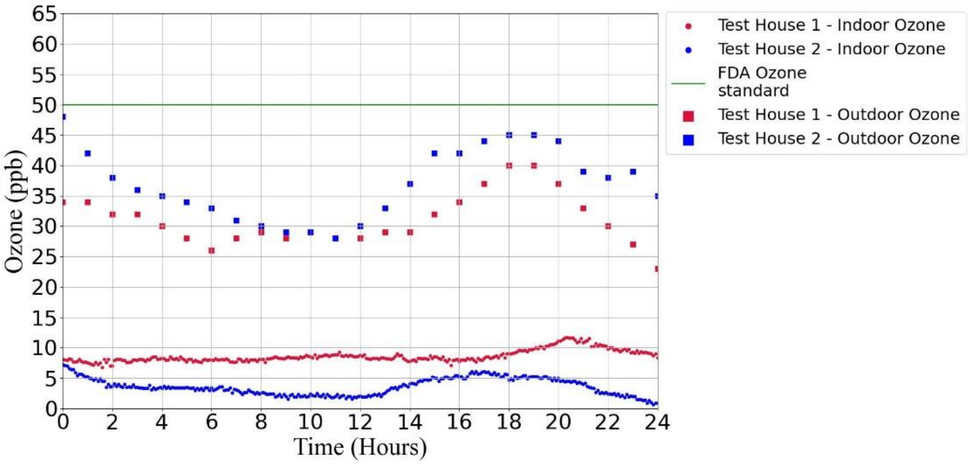


Figure 6. Ozone experiment 2 results for test houses #1 and #2

Both houses are identical in layout, window to wall ratio, and size (factors related to infiltrations in a house envelope discussed in *2.1.5 Infiltration of outdoor ozone into an indoor environment*) with the only difference being that house #2 has a tighter envelope than house #1. Therefore, it can be expected that house #2 will have lower indoor ozone levels than house #1. As seen in the data from Figure 6, the indoor ozone levels in house #2 followed outdoor levels at a low concentration (around an average of 3.6±1 ppb), while the indoor levels in house #1 had a higher concentration (around an average of 8.6±1 ppb).

Figure 7 shows normalized results of both houses in continuity, where the vertical black line separates house #2 (hours 0-48) and house #1 (hours 48-168). The indoor and outdoor ozone levels are normalized in a range from zero to one in percentage of their highest value seen from house #1 and house #2. Figure 7 also includes the I/O ratios of both houses in continuity.

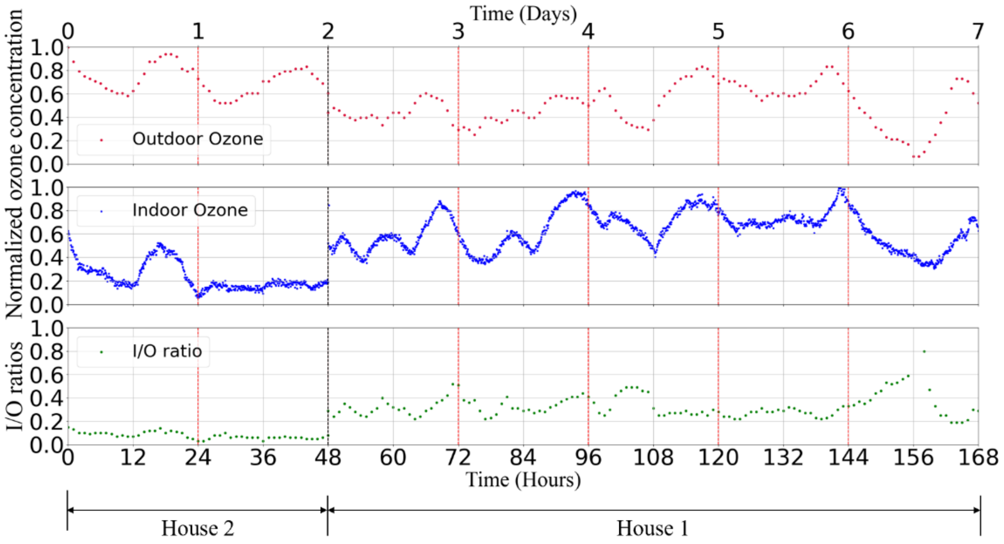


Figure 7. Normalized baseline indoor ozone levels for test house #1 (0-48 hours) and house #2 (48-168 hours)

Figure 7 provides a different visual for the same trends illustrated in Figure 6. House #2 is more air-tight, so the indoor ozone levels follow the outdoor ozone levels at a lower concentration than after the 48-hour mark when the ozone monitor was moved to test house #1. This is also represented by the increase in I/O ratio values after the sensor was moved to house #1. The results of ozone experiment 2 further highlight the tightness of house #2, with respect to the infiltration of outdoor ozone indoors which was an observation already seen with the results of ozone experiment 1.

3.4.3 Indoor ozone levels with mechanical ventilation in UTT house #2 (Ozone experiment 3)

Ozone experiment 3 was performed in test house 2 with the sensor located on a stool in the living room, and with the use of mechanical ventilation. Figures 8 and 9 shows the results of ozone experiment 3 for both ES air cleaners.

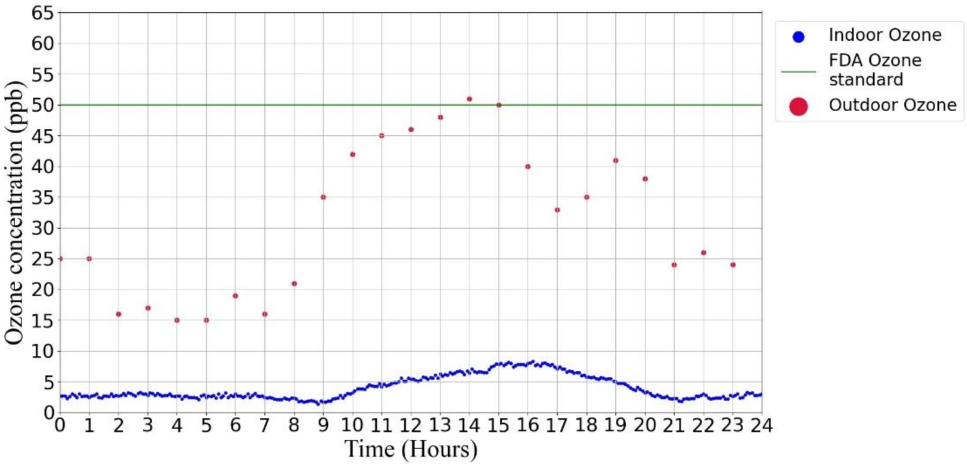


Figure 8. Ozone experiment 3 results during ES air cleaner A's testing

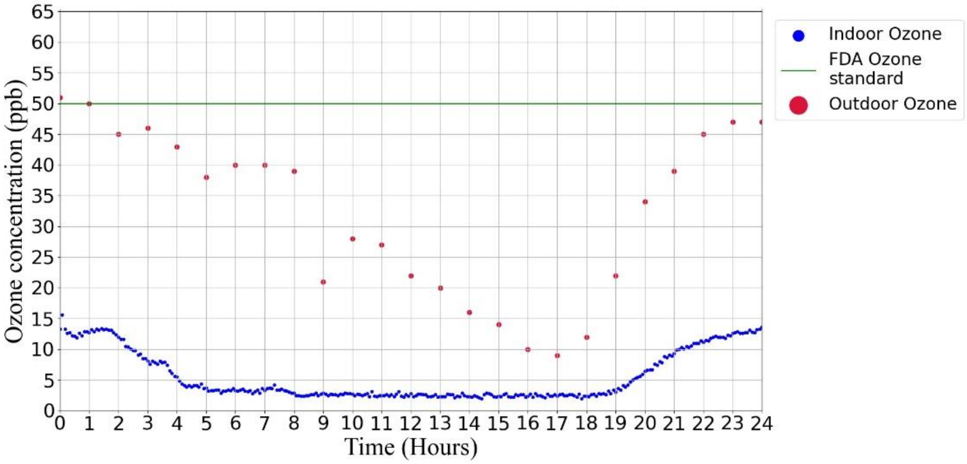


Figure 9. Ozone experiment 3 results during ES air cleaner B's testing

As discussed in *2.1.5 Infiltration of outdoor ozone into an indoor environment*, infiltration through mechanical ventilation and natural ventilation (through the opening of windows and doors) leads to higher I/O ratios. Ozone experiment 3 observes indoor ozone levels in test house #2 based on the influence of mechanical ventilation. With intake and exhaust ventilators being powered on, outdoor air is being directly introduced into the test house which has higher levels of ozone that is being mixed with indoor air. This causes the indoor ozone level trends to follow outdoor ozone level trends more closely, as seen in the plots. Quantitatively, the two tests included correlation coefficients of $R^2 = 0.52$ and $R^2 = 0.61$ between indoor and outdoor ozone. These coefficients are both higher that the coefficient in ozone experiment one (baseline ozone levels) $R^2 = 0.47$. In terms of magnitude, the I/O ratio increases from the baseline indoor ozone levels. The I/O ratios in ozone experiment 3 for ES cleaners A and B were 0.13±0.4 and 0.17±0.05, respectively. These ratios are both increases from ozone experiment 1 which had an I/O ratio of 0.08±0.03. In terms of observing the plots, one can see higher peaks (hour 16 in Figure 8 and hours 0 and 24 in Figure 9) of indoor ozone levels in ozone experiment 3 as opposed to the peak in indoor ozone levels (hour 17 in Figure 5) seen in ozone experiment 1. The results of ozone experiment 3 are later compared to the results of ozone experiment 4 to observe increases in indoor ozone levels due to the powering on of the ES air cleaners during a period with mechanical ventilation.

3.4.4 Indoor ozone levels with mechanical ventilation and the powering on of two ES air cleaners in UTT test house #2 (Ozone experiment 4)

Ozone experiment 4 was performed in test house 2 with the sensor located on a stool in the living room, and with the use of mechanical ventilation. The ES cleaners were powered on. Figures 10 and 11 show the indoor ozone data for ozone experiment 4, which had durations of 24 hours for ES air cleaners A and B, respectively.

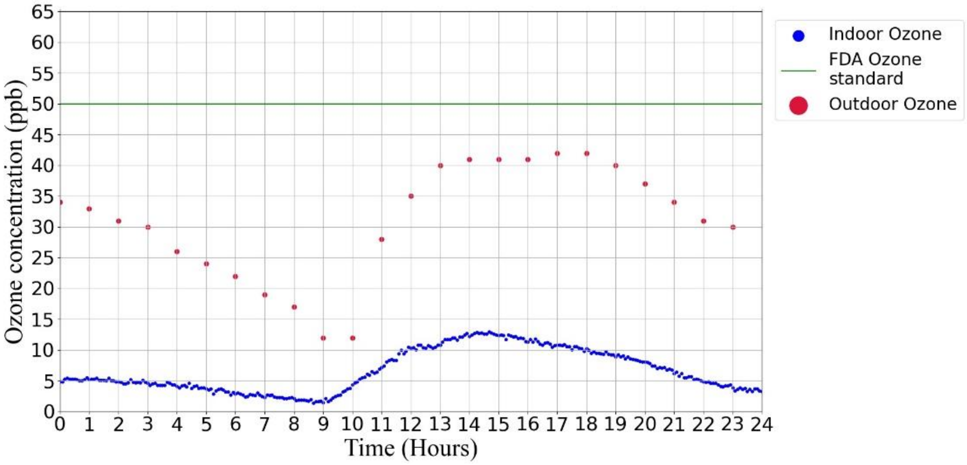


Figure 10. Ozone experiment 4 results during ES air cleaner A's testing

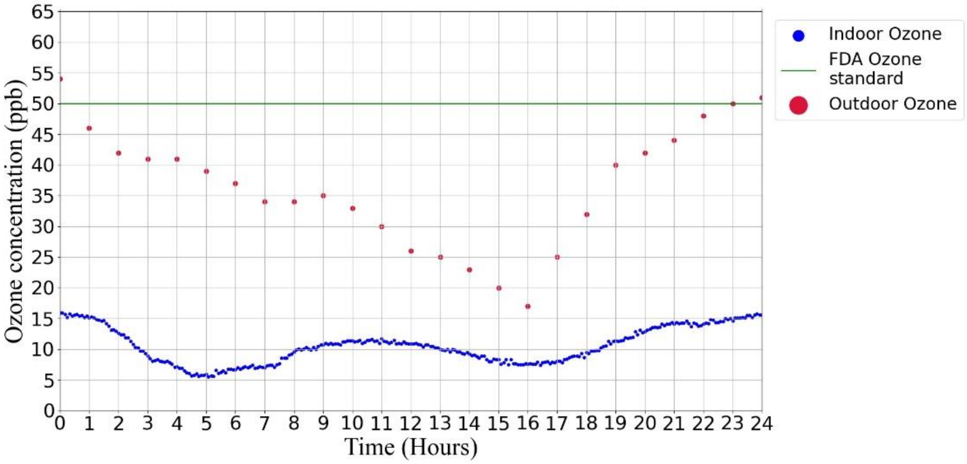


Figure 11. Ozone experiment 4 results during ES air cleaner B's testing

In ozone experiment 4, outdoor ozone is still being directly introduced into the test house through mechanical ventilation. There is such an indication when comparing the plots of ozone experiments 3 and 4 for ES air cleaner A (Figures 8 and 10). Even though lower outdoor ozone levels are seen in ozone experiment 4 in comparison to experiment 3, the indoor ozone levels in the house were higher. This distinction was also seen in the testing of ES air cleaner B (Figures 9 and 11). Quantitatively, comparing ozone experiments 3 and 4, increases in indoor ozone levels were seen of 2.6±2 ppb during the testing of ES air cleaner A and 5±2 ppb during the testing of

ES air cleaner B. Changes in outdoor ozone levels included a decrease of 0.2±9 ppb during the testing of ES air cleaner A and an increase of 4.2±9 ppb during the testing of ES air cleaner B. The I/O ratios in ozone experiment 4 for ES cleaners A and B were 0.21±0.05 and 0.29±0.05, respectively. These ratios are both increases from the I/O ratios in ozone experiment 3 which were 0.13±0.04 and 0.17±0.05 for ES air cleaners A and B, respectively. In both cases there is an indication of increases in indoor ozone due to the powering of the ES static air cleaners. However, it is uncertain what percentage of the increase was due to the ES air cleaners or the influence of mechanical ventilation. The comparison shows that neither ES air cleaner, in combination with mechanical ventilation, exceeded the FDA limit for ozone levels.

3.4.5 Indoor ozone levels with the powering on of ES air cleaners in UTT test house #2 (Ozone experiment 5 and 6)

Ozone experiment 5 was performed in test house 2 with the sensor located on a stool in the living room, without the use of mechanical ventilation. The ES cleaners were powered on. The results from ozone experiment 5 are shown in Figures 12 and 13 for ES air cleaners A and B, respectively.

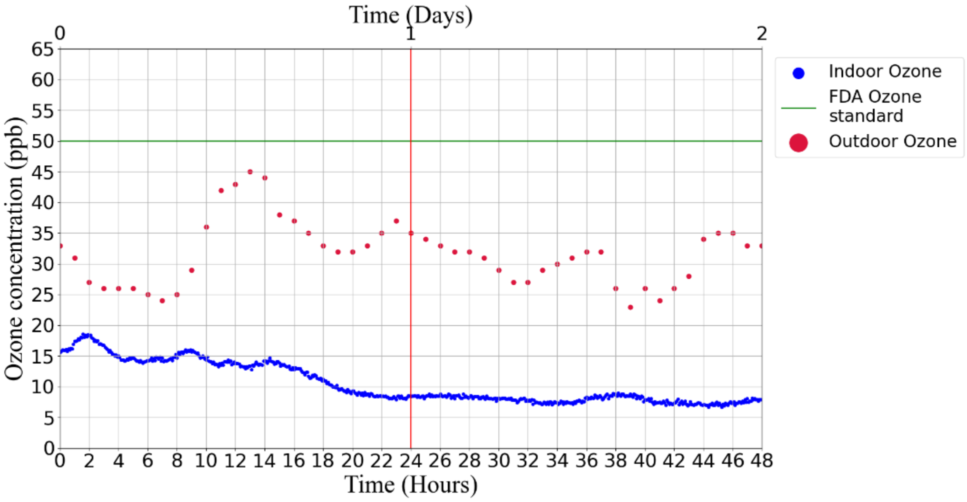


Figure 12. Ozone experiment 5 results during ES air cleaner A’s testing

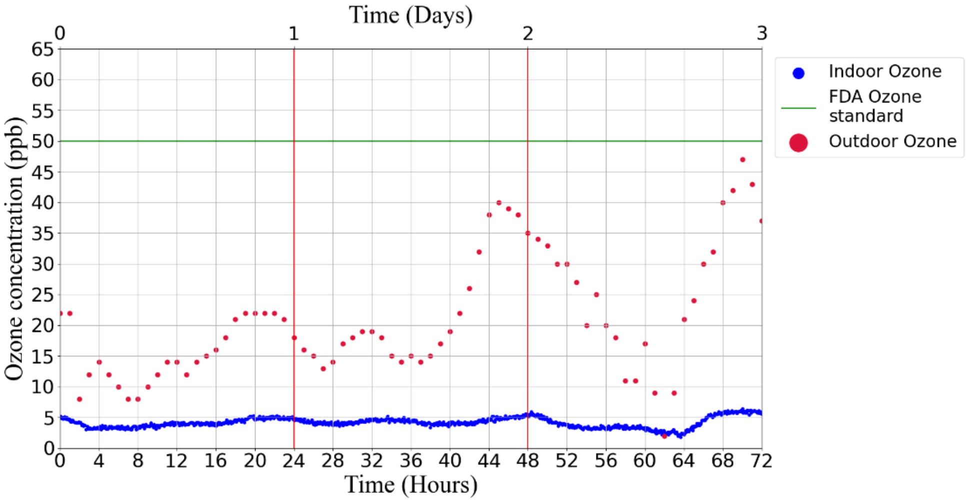


Figure 13. Ozone experiment 5 results during ES air cleaner B's testing

Ozone experiment 5 allows for a more direct evaluation of the contribution that the ES air cleaners had in raising indoor ozone levels. In experiment 5, the only indoor sources of ozone are the ES air cleaners with indoor ozone levels being influenced by outdoor levels solely through infiltrations. This allows for a distinct comparison between the indoor levels from ozone experiment 1 and experiment 5. For ES air cleaner A, the inside ozone levels varied around an average of 10.5±1 ppb (Figure 12) where in ozone experiment 1 they varied around an average of 2.7±1 ppb (Figure 5). ES air cleaner A, on max setting, increased the ambient ozone levels in the house by approximately 7±2 ppb. ES air cleaner B increased the indoor ozone concentration only minimally from baseline ozone levels. ES air cleaner B contributed to indoor ozone levels that varied around an average of 4.2±1 ppb (Figure 13) leading to an approximate increase of approximately 1.5±2 ppb. Decreases in outdoor ozone levels between experiments were 3±3 ppb during the testing of ES air cleaner A and 13.8±4 ppb during the testing of ES air cleaner B. The I/O ratios in ozone experiment 5 for ES cleaners A and B were 0.33±0.05 and 0.2±0.08, respectively. These ratios are both increases from ozone experiment 1 which had an I/O ratio of 0.08±0.03.

As stated in *2.1.6 Generation of ozone from ES air cleaners*, ES air cleaners ionize incoming contaminant particles by generating a field of static electricity. In search of further reducing contaminant particles, different ES air cleaners will generate higher fields of static electricity based on respective design factors and/or higher operation options. Since ES air cleaner A has a “maximum-on” operation option while ES air cleaner B has an “on” option only, it is expected that ES air will generate more ozone due to a higher operation level of ionization. It is also important to note that the increases seen with ES air cleaner A and B were at the lower end of the 10-77 ppb increases mentioned in *2.1.6 Generation of ozone from ES air cleaners*.

Both air cleaners contributed to an increase in indoor ozone concentrations even with decreases in outdoor ozone levels. The statistical significance of the results was found with a hypothesis test for the difference of means. This included the computation of a p-value which describes the probability of the test reaching the null hypothesis, which is described below. The averages of indoor ozone for experiment 5 of both ES air cleaners (where the ES air cleaners were the only source of indoor ozone) were compared to the average of indoor ozone in experiment 1 (baseline ozone levels). In order to compare the ES air cleaners together, data was taken from the first 48 hours of ES air cleaner A’s experiment 5 to match the sample size of ES air cleaner B’s experiment 5. The null hypothesis was that the ES air cleaners did not contribute to higher ozone levels than baseline ozone levels. Both ES air cleaners had p-values of less than 0.00001 when compared to baseline indoor ozone levels, which leads to the data results being statistically significant to a significance level of 95%. This led to the conclusion that the average indoor ozone concentration was actually higher when the ES air cleaners were powered on and that it was not due to chance. Nevertheless, the increase in indoor ozone from either of the ES air cleaners did not exceed the FDA 21CFR801 standard of 50 ppb mentioned in the *Introduction.*

Ozone experiment 6 was performed in test house 2 with the sensor located on a ladder in the living room, without the use of mechanical ventilation. The ES cleaners were powered on. The results of the final ozone experiment, experiment 6, are shown in Figures 14 and 15 for ES air cleaners A and B respectively.

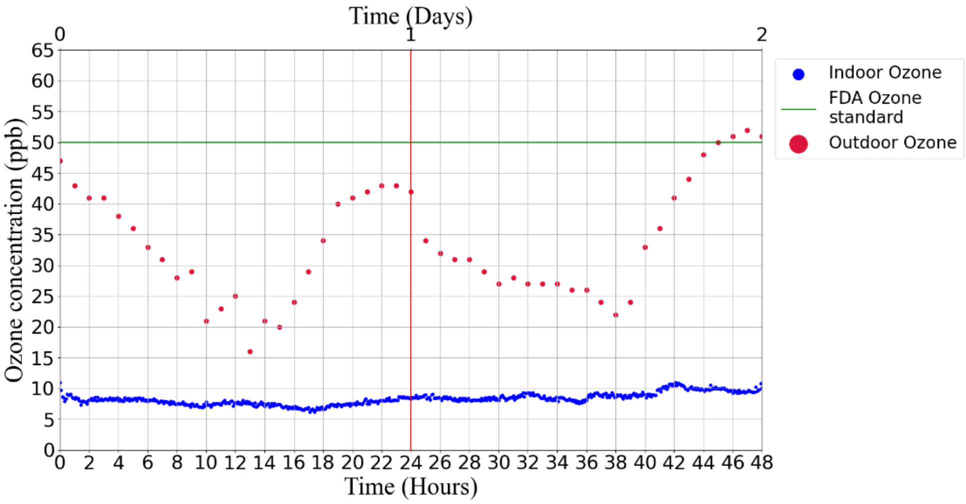


Figure 14. Ozone experiment 6 results during ES air cleaner A's testing

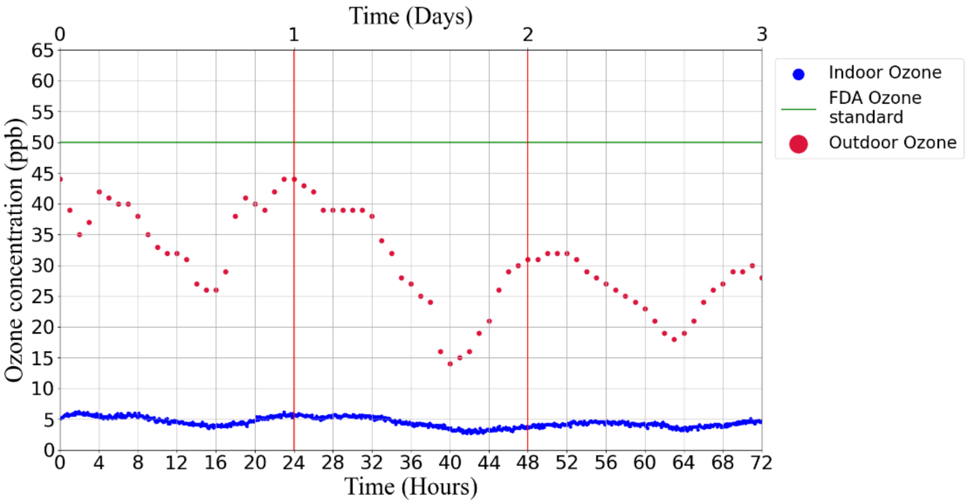


Figure 15. Ozone experiment 6 results during ES air cleaner B's testing

Ozone experiment 6 focuses on the differences in indoor ozone levels observed near the supply registers than when observed in the living space. The idea is that since the ES air cleaners are producing a by-product of ozone, ozone levels should be higher near the supply registers before diluting into the air of the living space. However, this did not seem to be the case. Changes in indoor ozone levels between ozone experiments 5 to 6 included a decrease of 2.2±2 pbb during the testing of ES air cleaner A and a slight increase of 0.3±2 pbb during the testing of ES air cleaner B. Increases in outdoor ozone levels between experiments were 2±4 pbb during the testing of ES air cleaner A and 9.9±4 pbb during the testing of ES air cleaner B. The I/O ratios in ozone experiment 6 for ES cleaners A and B were 0.25±0.04 and 0.15±0.04, respectively. These ratios are both decreases from the I/O ratios in ozone experiment 5 which were 0.33±0.05 and 0.20±0.08 for ES air cleaners A and B, respectively. Referring back to the plots, the indoor ozone for both ES air cleaners (Figures 14 and 15) seemed to remain very close to the indoor levels in ozone experiment 5 (Figures 12 and 13), when the sensor was on a stool. This concept is re-enforced in the stratification of ozone test discussed in *Appendix B.*

3.5 Conclusions from ozone experiments

Both ES air cleaners contributed to increases in indoor ozone levels in test house #2. ES air cleaner A showed an increase in ozone magnitude from 2.7 to 10.5 ppb (approx. 7±2 ppb), while ES air cleaner showed a minimal increase from 2.7 ppb to 4.2 ppb (approx. 1±2 ppb). These results were statistically significant with very low p-values. In terms of increases in I/O, ES air cleaner A showed an increase of 0.25±0.02, while ES air cleaner B showed an increase of 0.12±0.05. Even though the ES air cleaners were found to give off a by-product of ozone, neither of the ES air cleaners surpassed the indoor limit of ozone based on the FDA standard 21CFR801 with ES air cleaners A and B being 39.5 and 45.8 ppb below the 50-ppb ozone limit, respectively. It is also noteworthy that the indoor ozone levels observed at the supply registers were not noticeably higher than ozone levels measured at the living space, confirming the stratification test in *Appendix b*. The ES air cleaners also increased indoor ozone levels during a period where test house #2 was being mechanically ventilated. Nevertheless, neither of the ES air cleaners, in combination with mechanical ventilation, raised indoor ozone levels above the FDA limit with ES air cleaners A and B being 43.4 and 39.4 ppb below the 50-ppb ozone limit, respectively.

These findings contribute to determining the safety of using ES air cleaning technology in residential applications. Thus, providing information that will assist consumers in making decisions on IAQ mitigation strategies and help manufacturers in the future development of ES air cleaning technology in residential applications. Additional findings include that the powering on of ventilation led to the indoor ozone levels being more correlated to outdoor ozone, and that indoor ozone levels seen in test house # 2 were lower than those seen in test house #1, which had the draftier insulation.

CHAPTER 4 – CORRECTION MODEL FOR CLIMATIC VARIABLES AFFECTING VOC READINGS

4.1 Overview of multi-pixel gas sensors

In this thesis, Element AWAIR sensors were used to measure VOC concentrations in the VOC experiments performed at the UTT test homes. The AWAIR element sensors use a multi-pixel metal oxide as their respective sensing element. In a review of low-cost sensors for indoor air quality, Garcia et al. [47] discuss the technology and components used in sensors to read VOCs which includes metal oxide semiconductors or MOS [47]. Garcia et al. [47] state that based on laboratory and on-field studies, it is known that MOS sensor sensitivity varies due to temperature and humidity. Another paper written by Abdullah et al. [48] is even more specific [48]. Abdullah et al. [48] write that the method for which the MOS sensors read VOCs is through the adsorption of VOCs on the device's sensing material. Temperature and humidity will both affect the adsorption of VOCs onto the sensor's sensing material. With an increase in temperature, there is an increased adsorption of oxygen on the sensing material which causes a decrease in sensitivity in the sensor's reading. An increase in humidity will cause water vapor to adsorb onto the sensing material causing a "drift" in the sensor's readings.

According to testing done by Abdullah et al. [48], observing sensor responses due to temperature and humidity, it was found that the two environmental variables are inversely related with sensor resistance. Achieving a steady-state VOC concentration, increases in temperature and humidity led to decreases in sensor resistance while decreases in temperature and humidity lead to an increase in sensor resistance. A decrease in sensor resistance leads to higher VOC concentration readings that is unrelated to any injections of VOCs in the test chamber while an increase in sensor resistance would lead to the opposite effect [49]. Therefore, with this sensor technology, variations in temperature and humidity will lead to variations in VOC readings that are unrelated to actual changes in VOC concentrations.

4.2 Effect of temperature and humidity on VOC sensor readings

A baseline was run at the test house in a period of time where no VOCs were injected into the UTT test home. During this period, the thermostat was manipulated to cool and subsequentially heat the house to observe changes in sensor VOC readings due to changes in temperature and humidity. Figure 16 shows the results of the baseline with labels for when the thermostat was manipulated.

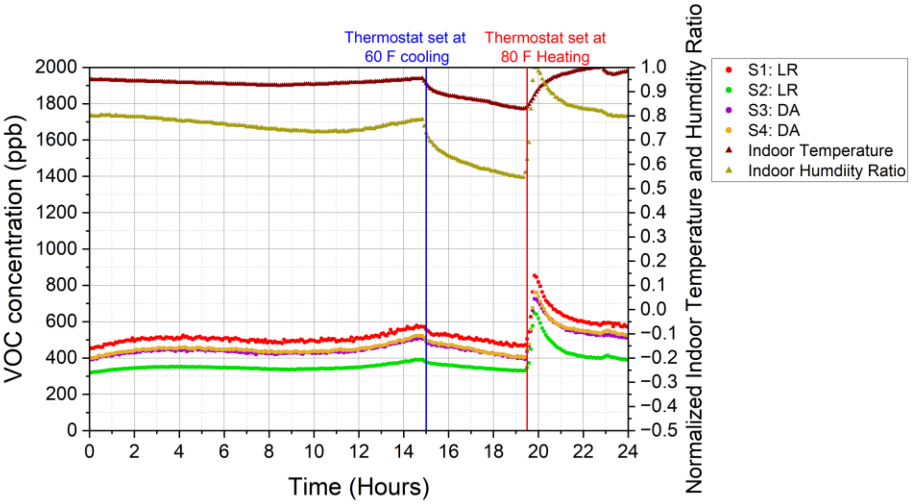


Figure 16. Variations in VOC concentrations due to temperature and humidity

Ideally, it is expected that since no VOCs are injected into the house during this period of time, the VOCs would vary minimally and remain close to a constant. However, it can be seen in Figure 16 that as the thermostat is set on cooling mode, the VOC concentrations immediately start to decrease as both climatic variables start to decrease. When the thermostat is changed to heating mode, an immediate spike is seen in humidity leading to a spike in VOC concentrations even though no VOCs were injected. This baseline reveals a couple of things regarding the effect of the climatic variables on the VOC sensor readings. One is that variations in temperature and humidity cause immediate variations in VOC sensor readings that are unrelated to actual changes in VOC concentrations. The second is that variations in humidity have a greater effect on variations in VOC concentrations than temperature. This can be seen at hour 19.5 where there was a spike in VOC concentrations corresponding to the spike in humidity as opposed to a gradual increase as seen with temperature. Specifically, in the VOC spike between hour 19 and 19.83, a 90% increase in VOC concentration was seen corresponding to increases in temperature and humidity of 6% and 82%, respectively.

In the main VOC experiments, the compressor of the HVAC was powered off which means the house was not thermoregulated. Indoor temperature and humidity varied naturally based on the outdoor conditions, mainly due to infiltration. Overall, as can be seen with the information from *4.1 Overview on multi-pixel sensors* and the baseline presented in this section, the variations in VOC concentrations due to the climatic variables were required to be corrected in order to see the true trends in VOC concentrations.

4.3 Methodology for VOC correction model

To combine the effects of temperature and humidity into a single variable, the total enthalpy of the air was used to represent the complex interactions of the climatic variables for the development of the correction model. The formula used for total enthalpy of the air is shown in Equation (3) from the ASHRAE fundamentals handbook IP 2017 where T is temperature in °F and ω is the humidity ratio [50]. These enthalpy values are associated to each individual reading of VOC concentration to be used for the implementation of the model.

$$h = 0.24 + \omega(1061 + 0.444T) \qquad \textit{Equation (3)}$$

The correction model works to observe variations in VOC concentrations due to variations in enthalpy and remove those effects. The results of each VOC experiment are a corresponding decay from a spike in VOC concentration due to the injection of VOCs. The effects of enthalpy on the decay were evident as “humps” in VOC concentration were seen. One of the results of the VOC experiments is shown in Figure 17 to illustrate the previously stated behavior. The final plots of uncorrected and corrected experimental data are in *Results and discussion of VOC experiment.*

To determine the specific effect that enthalpy had on each experiment, a period of the data at the end of the decay that included a “hump” was taken (outlined in a red box in Figure 17) where the VOC concentration is expected to be constant (i.e., is not expected to change).

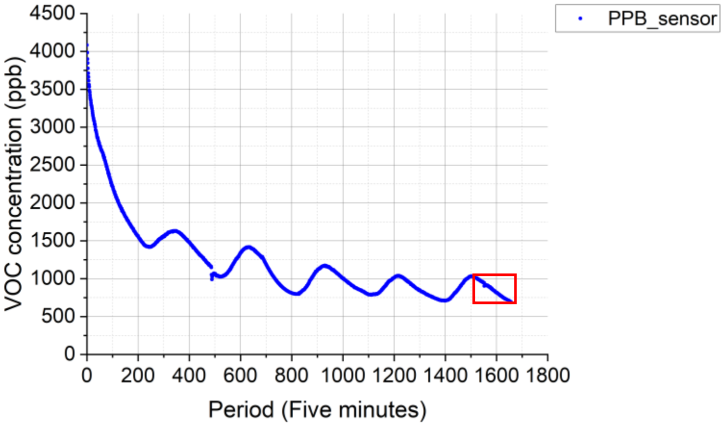
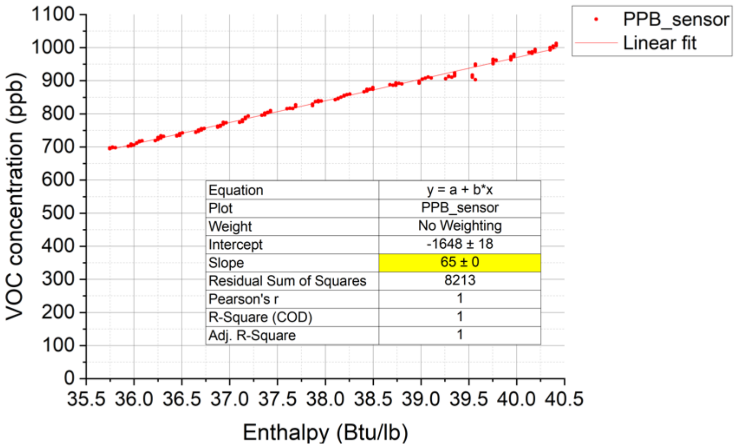


Figure 17. Uncorrected VOC data

During this period of time (outlined by the red box), VOC concentrations are plotted against enthalpy values. A linear trendline is then computed to obtain the slope (*M*) which characterizes the change in VOC concentrations according to enthalpy as seen in Figure 18.



Equation	y = a + b*x
Plot	PPB_sensor
Weight	No Weighting
Intercept	-1648 ± 18
Slope	65 ± 0
Residual Sum of Squares	8213
Pearson's r	1
R-Square (COD)	1
Adj. R-Square	1

Figure 18. Calculation of slope to be used in correction model procedure

According to the corresponding variation in enthalpy of every VOC concentration reading, the slope was used as a correction coefficient. Variations in enthalpy from the main data set were computed by calculating the difference in every value of enthalpy and the initial value of enthalpy. The product of the calculated slope to the calculated variation in enthalpy corresponding to each data point is characterized as the correction factor for every data point (denoted as F_n). To obtain the new corrected VOC concentration, the correction factor (F_n) for every data point is subtracted from the original reading from the sensor. It is important to note that not all data points were selected to be inputted into the correction model. The data selected included the initial decay of VOCs, where no “humps” in the data were seen, in addition to the lowest points in the “dips” seen in the original data set. The overall procedure of the correction model is summarized in Table 9.

Table 10. Overview of correction model procedure

Step	***Implementation***
1. Obtain the slope (*M*) characterizing the change in VOC concentration to enthalpy.	• Take the period of the data at the end of the decay that includes the last "hump," where the VOC concentration is expected to be constant. • Plot VOC concentration vs enthalpy during that period to get the slope (*M)* from a linear trendline.
2. Calculate the variations in enthalpy.	• $\Delta h_n = h_n - h_i$ • Where h_n is the enthalpy corresponding to a sensor reading. • Where h_i is the initial enthalpy read.
3. Calculate the correction factor for every data point.	• $F_n = M \times \Delta h_n$ • Where F_n is the correction factor for a data point.
4. Calculate the new corrected VOC concentrations.	• $PPB\_M = PPB\_sensor - F_n$ • Where PPB_sensor is the VOC concentration reading from the sensor. • Where PPB_M is the new corrected VOC concentration reading.

To further clarify the procedure used in correcting a VOC reading from the AWAIR sensor, a numerical example for steps 2 through 4 is given below in Table 10 (using the same notation from Table 9). Two concentration readings from the sensor, an initial concentration reading at the beginning of the decay (say 1000 ppb) and the next concentration reading (say 900 ppb), are given. Example corresponding enthalpy values to those concentration readings are given as well (computed by the temperature and relative humidity read by the sensor). In this example, the initial enthalpy value (h_i) would be 32.4 $\frac{Btu}{lb}$. This value would be used to subtract from each enthalpy value (h_n) in the data set. The initial concentration would therefore not be corrected, which would also be the case for any concentration reading which had an enthalpy value equal to the initial enthalpy value. In the case of the following concentration reading (900 ppb) of the example, it would have a corrected concentration value as there is a difference in its enthalpy value from the initial value. That difference ($\Delta h_n = h_i - h_2$) would then be multiplied by the calculated slope for that set of data $\left(say\ M = 65\,\frac{ppb}{\frac{Btu}{lb}}\right)$. This would then be the correction factor (F_n) which would be subtracted from the original concentration reading (PPB_sensor) to give the corrected concentration (PPB_M).

Table 11. Example of correction model procedure

PPB_sensor (ppb)	h_n $\left(\frac{Btu}{lb}\right)$	Δh_n $\left(\frac{Btu}{lb}\right)$	F_n (ppb)	PPB_M (ppb)	M $\left(\frac{ppb}{\frac{Btu}{lb}}\right)$
1000	32.4	$32.4 - 32.4 = 0$	$0 \times 64 = 0$	$1000 - 0 = 1000$	65
900	32.6	$32.6 - 32.4 = 0.2$	$0.2 \times 64 = 12.8$	$1000 - 12.8 = 987.2$	

This approach, and the result of implementing the correction model is shown in Figure 19.

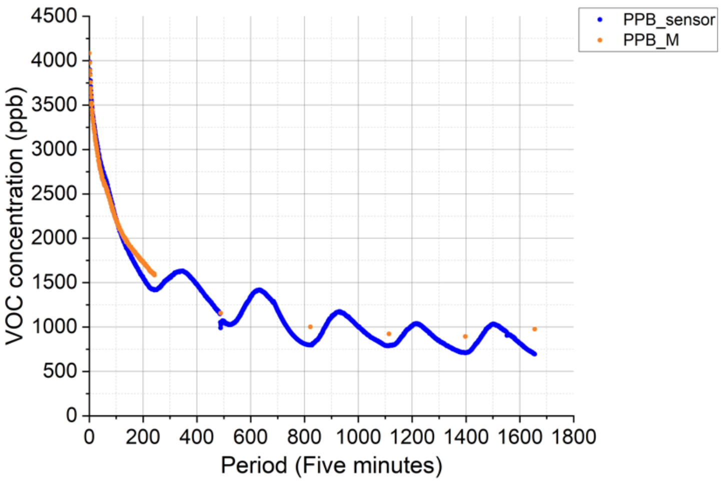


Figure 19. Corrected VOC data

The newly corrected VOC plot represents the VOC concentration unaffected by enthalpy (combining the effects of temperature and humidity). Since the number of data points was reduced with the implementation of the correction model, a trendline was needed to characterize the entire period of decay for each experiment. According to existing studies tasked with developing an empirical formula for the behavior of VOC decay (discussed later in this section), the function used to describe the decay of VOCs is a double exponential decay function as seen generally with Equation (4).

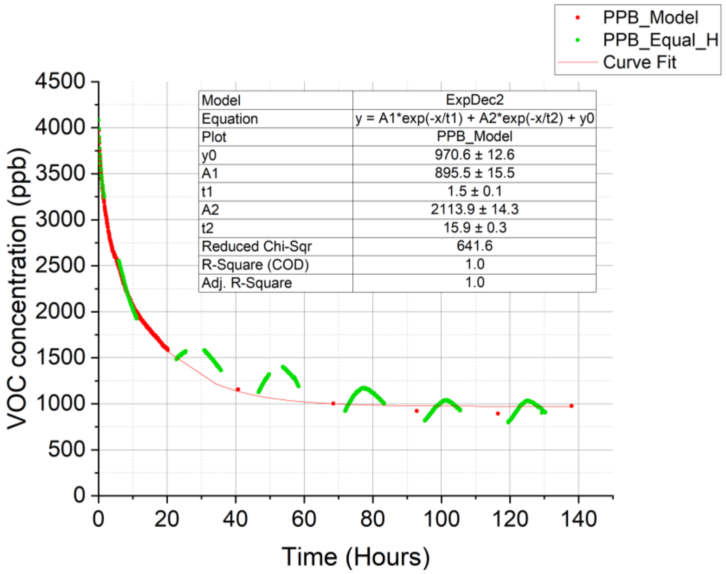
$$A_1e^{-bx} + A_2e^{-dx} + y_o;\ where\ b = \frac{1}{t_1}\ and\ d = \frac{1}{t_2} \qquad Equation\ (4)$$

A double exponential function is able to represent the combination of the initial steep decay and latter gradual decay seen in overall VOC decays. It is important to note that the y_o value is incorporated to represent the fact that there is a background level of VOCs already in the house and that the decay will not necessarily go to zero.

As stated previously, there is available literature that provides some insight into an empirical model that can describe the decay of VOCs and support the use of a double exponential decay function curve fit with a y_o value. One paper by Zhang et al. [51] was tasked with the creation of an empirical model of VOC emissions from indoor building emissions in an environment chamber. The paper derived an equation which resulted in a double exponential decay. However, it did not include a y_o because it assumed that the chamber did not have background VOCs [51]. In another paper that derived an empirical model for prediction of VOC concentration, did so considering a real indoor environment. This study did consider background VOC levels and derived a double exponential formula with a y_o value [52].

Using the same data set selected to illustrate the implementation of the correction model in this section, Figure 20 shows the result of using a double exponential decay function as a curve fit.

Also included is a separated set of data used to verify the curve fitted corrected data. The verification data used is the data points from the original sensor readings where the enthalpy is the same as the initial enthalpy value. All of the verification plots for the results of the VOC experiments are given in A*ppendix E.*



Model	ExpDec2
Equation	y = A1*exp(-x/t1) + A2*exp(-x/t2) + y0
Plot	PPB_Model
y0	970.6 ± 12.6
A1	895.5 ± 15.5
t1	1.5 ± 0.1
A2	2113.9 ± 14.3
t2	15.9 ± 0.3
Reduced Chi-Sqr	641.6
R-Square (COD)	1.0
Adj. R-Square	1.0

Figure 20. Curve fit of corrected data including verification data

As can be seen with Figure 20, the curve fit function touches the majority of the validation data sections (PPB_Equal_H) while reasonably representing the decay trend following the VOC injection.

4.4 Comparison of corrected data and uncorrected data

Now that the respective curve fit is found, representing the corrected VOC data, it can be compared to the original sensor VOC data as shown in Figure 21.

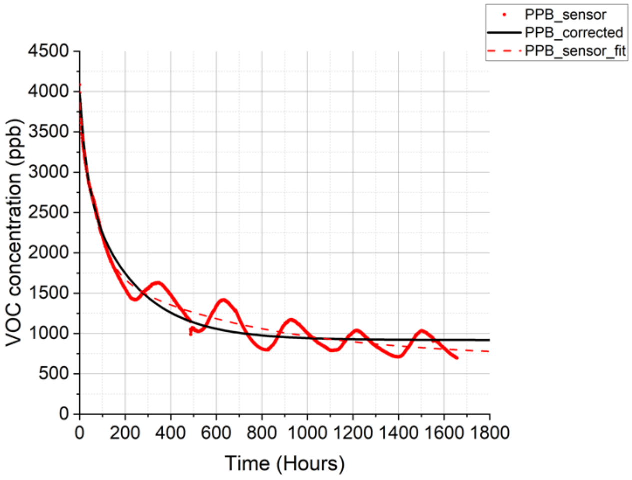


Figure 21. Uncorrected sensor VOC readings versus corrected data

The curve fit representing the corrected VOC data is able to show the estimated true decay of the VOCs in the test house without any of the humps caused by variations in enthalpy. This is in addition to shifting the VOC data to represent the estimated true decay of VOCs by removing the effects of enthalpy, which can be seen by comparing the curve fits of the corrected (PPB_corrected) and uncorrected data (PPB_sensor_fit).

4.6 Conclusion of climatic correction model

Through available literature review, it was known that VOC sensor readings varied depending on variations in temperature and humidity unrelated to actual changes in VOC concentrations. This is in addition to an independent observation presented in this thesis in the form of a baseline conducted in the UTT test home where no VOCs were injected that showed variations in VOC sensor readings due to temperature and humidity. In this case, a correction model was developed to remove those effects and produce the actual trends in VOC concentrations. The two environmental variables (temperature and humidity) are combined into a single variable (enthalpy) to improve the performance of the correction model. The procedure for implementing the correction model and its development were discussed in this section. Overall, the correction model was able to produce a new, reasonable data set of VOC concentrations with minimized variations due to environmental variables. This is in addition to a curve fit that could characterize the newly corrected set of data.

CHAPTER 5 – METHODOLOGY AND RESULTS FOR THE EVALUATION OF PCO EFFECTIVNESS

5.1 Testing facilities for VOC experiments

The VOC experiments were conducted in one of two research houses at the University of Texas at Tyler (UTT) named test house #2 (characteristics given in *3.1 Testing Facilities*). For the VOC experiments, Figure 23 illustrates the layout of the IAQ sensors used in test house #2.

5.2 Overview of AWAIR IAQ sensors

The IAQ sensors used in the VOC experiments include the AWAIR Element residential monitor. Three of the five available variables the sensors can read are used which includes temperature, relative humidity, and VOC concentration. Both temperature and relative humidity are read using the complementary metal-oxide semiconductor sensor (CMOS) included in the AWAIR device. The technical accuracy of the temperature readings are ±0.2℃ with a resolution of 0.015℃, while the technical accuracy of the relative humidity readings is ±2% RH with a resolution of 0.01% RH. VOCs concentrations are read using the Sensirion SGP30 multi-pixel metal oxide gas sensor integrated in the AWAIR device with a technical accuracy of 15% with a 1ppb resolution. It is important to note that VOC readings given by the AWAIR device are total concentrations of VOCs in the air as the sensor does not give the concentrations of individual VOCs. The list of VOCs the AWAIR monitor can read is an extensive but not exhaustive list that is listed on the manufacturer's website [53]. The AWAIR monitors record values every 5 minutes with data being constantly uploaded to the AWAIR cloud [54]. In terms of recalibration, before every VOC experiment, the AWAIR Element sensors underwent a reset procedure which is discussed in *Appendix C*.

The AWAIR sensors were placed on a stool in the center of every room excluding the kitchen and bathroom as seen in Figure 22. Due to the open concept of the test house, one AWAIR sensor was placed in the living room while another was set in the dining room area. The horizontal and vertical placement of the AWAIR sensors in each room was a result of two of reference guidelines for measuring VOCs indoors (see *Appendix B*). Figure 3 shows the location of the AWAIR sensors with respect to the house layout.

Figure 22. Stool setup for the AWAIR IAQ sensors

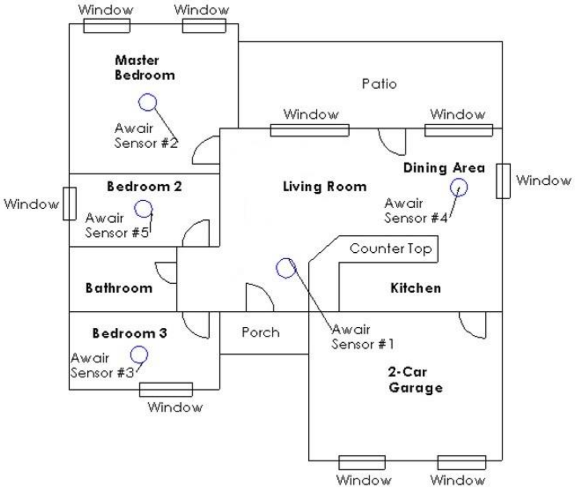


Figure 23. AWAIR sensor location and nearest supply registers in Test house #2

5.3 Experimental methods for VOC injection

The experiments differentiate themselves in terms of the VOCs that were injected, the power status of the PCO, and the PCO that was tested. For each VOC injected, the decay of VOC concentrations in the test house was observed under the operation of the PCO air cleaner being evaluated and when no PCO device was operating. This allowed for a direct comparison to be made of the decay of VOC spikes due to the PCO air cleaners themselves versus being due to the infiltration of fresh air diluting the VOCs. Two PCO air cleaners, A and B, were evaluated for each VOC, whose specifications are detailed in *5.5 Specifications of tested PCO air cleaners*. Both PCO devices being evaluated were installed in a plenum setup, attached to the air handling unit (AHU) located in the attic of the house which is shown in Figure 24. The plenum houses the air cleaner being tested and allows for the quick exchange of different air cleaners from experiment to experiment. Each air cleaner came in its own frame which included an in-duct filter.

Figure 24. Plenum setup used to evaluate PCO air cleaners

The VOCs used included two products containing VOCs and one pure VOC substance. The manner in which each VOC was introduced or injected into the air was different. However, the overall experimental procedure remained the same. In the experiments where no PCO air cleaners were evaluated, VOCs were injected in every room in order to reach an overall concentration in the whole house. Once that concentration was reached, the VOC concentrations were left to decrease due to natural decay. Before each experiment, the PCO air cleaner being evaluated would be installed in the plenum and powered on with the HVAC fan running in order allow the catalyst to regenerate and remove VOC residue from previous experiments for a period of 2.5 hours. The PCO air cleaner being evaluated would then be removed from the plenum and placed in the other test house that did not have VOCs injected into it, so that the VOCs could be injected in test house 2. Once the VOCs injected in every room raised the overall concentration in the house to the desired value, the PCO air cleaner being evaluated was re-installed in the plenum and powered on to observe the acceleration in VOC decay due to the PCO air cleaner. Table 12 is a T-chart summarizing the general procedure of the experiments.

Table 12. General procedure of experiments for PCO on/off status

PCO OFF	**PCO ON**
• VOCs are injected in the test house	• PCO is powered on, installed in the plenum, with the AHU fan running to regenerate the PCO catalyst for 2.5 hours
• Desired concentration is reached	• PCO is removed so that VOCs can be injected into the test house
• VOCs are allowed to decay naturally	• Desired concentration is reached
	• PCO is re-installed in the plenum and powered on

The first VOC product used to evaluate the PCO air cleaner was a flat black oil-based paint by Rust-Oleum with a high VOC content of 410 g/L, according to the product's safety data sheet (SDS) listed on the manufacturer's website [55]. This is in comparison to water-based or "low VOC" paint which generally has less than 50 g/L [56]. The specific list of VOCs that are included in the paint are not given in the SDS sheet as the document lists only a hydrotreated light distillate (a combination of hydrocarbons). The SDS sheet of the distillate also does not give the specific

VOCs included. However, the most common VOCs used in oil-based paint solvents include toluene, xylene, ethanol, and acetone as well as many others [57]. A picture of the paint is shown in Figure 25.

Figure 25. Rust-Oleum Flat black oil-based paint [58]

The paint was applied on pieces of cardboard laid out on top of poster boards. The poster boards were placed in front of each room’s AWAIR sensor. Three rounds of paint were injected in the following order in the test house: master bedroom, dining room, living room, bedroom 3, and bedroom 2. In the first two rounds, approximately 40% of the cardboard was painted over each round. In the last round, the remaining 20% was painted over. In rooms where the VOC concentration was not at the desired concentration, additional paint was applied on the cardboard pieces and surrounding poster board to reach the desired VOC concentration. The setup and progression of paint applications are shown in Figure 26.

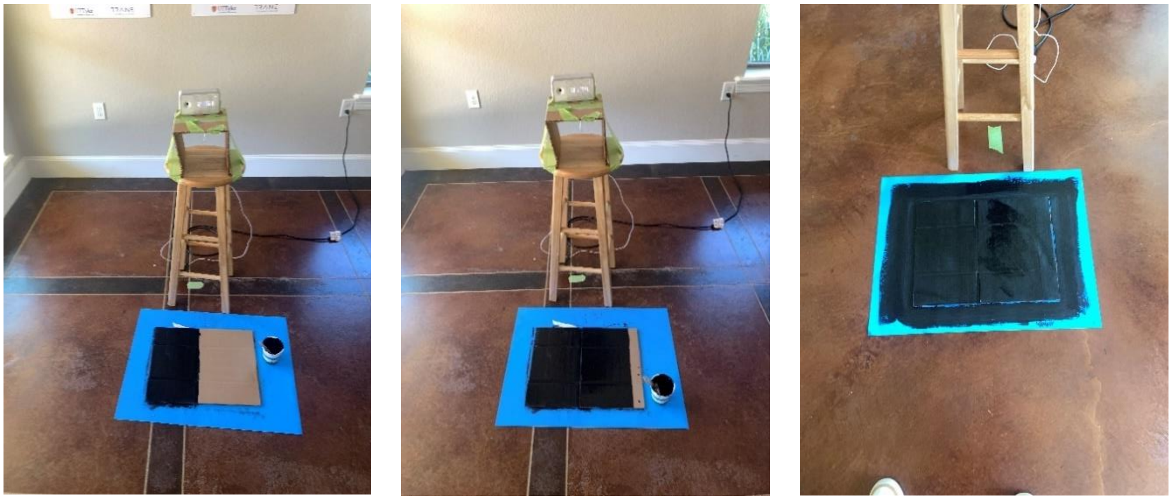


Figure 26. Setup for paint VOC injection

The second VOC product used to evaluate the PCO air cleaner was the Mr. Clean all-purpose cleaner with summer citrus. The safety data sheet (SDS) of the product does not give the specific percentage of VOC content and instead states that, “Products comply with US state and federal regulations for VOC content in consumer products [59].” The CPID (Consumer Product Information Database) gives the complete list of ingredients in the product. Some of the ingredients are considered as chemicals of concern with some ingredients being direct VOCs themselves including Sodium hydroxide, Geraniol, Hexyl Cinnamal, Citral, Citronellol, d-Limonene, and Linalool. The product is shown in Figure 27.

Figure 27. Mr. Clean all-purpose summer citrus [60]

As seen in Figure 28, a Styrofoam board piece was laid flat on a poster board in front of each AWAIR sensor in their respective areas. The Mr. Clean all-purpose cleaner was poured and spread over the board periodically for multiple cycles in the same order as the paint injection in order to reach the desired concentration in the whole house.

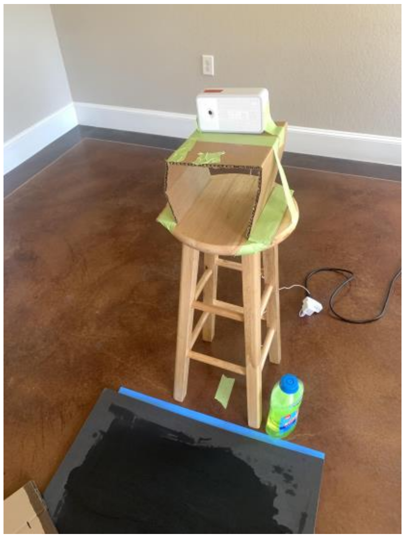


Figure 28. Setup for Mr. Clean all-purpose cleaner VOC injection

The last VOC product used to evaluate the PCO air cleaners was a spray bottle of pure d-limonene at 93-95% from Lab Alley [61]. The d-limonene bottle and spray bottles used to apply the substance in the house are shown in Figure 29.

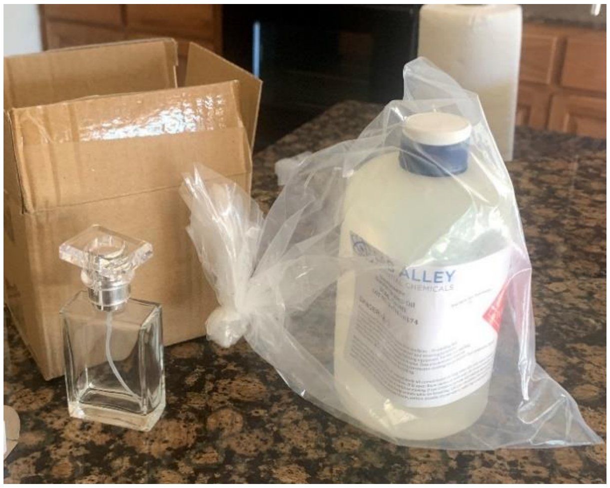


Figure 29. d-limonene bottle and spray bottle

For the d-limonene application, a white poster board piece was laid flat on the floor in front of each AWAIR in each room as seen in Figure 30. The d-limonene was first poured in the spray bottle. The spray bottle was then used to spray the VOC on the poster pieces periodically for multiple cycles in the same order as the paint and all-purpose cleaner injections in order to reach the desired concentration in the whole house.

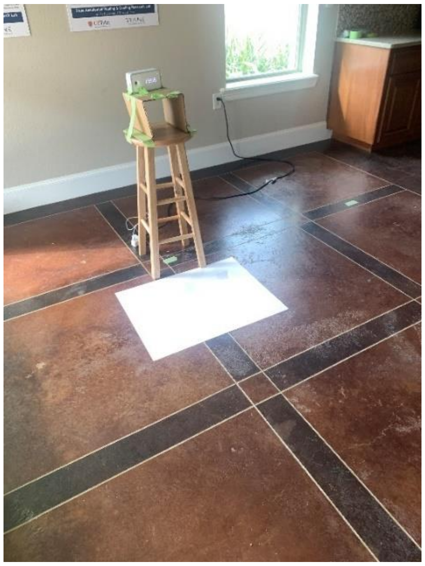


Figure 30. Setup for pure d-limonene VOC injection

In summary, each VOC product was injected to be evaluated without the operation of a PCO and with the operation of PCO air cleaner A and B respectively for a total of nine experiments as seen in Table 13. The table also includes the duration of each experiment.

Table 13. Description of VOC experiments with duration

Experiment No.	Description	Duration (hours - days)
1	Paint VOC injection without PCO air cleaner operating	144 – 6.0
2	Paint VOC injection with PCO air cleaner A operating	140 – 5.8
3	Paint VOC injection with PCO air cleaner B operating	72 – 3.0
4	All-purpose VOC injection without PCO air cleaner operating	144 – 6.0
5	All-purpose VOC injection with PCO air cleaner A operating	72 – 3.0
6	All-purpose VOC injection with PCO air cleaner B operating	70 – 2.9
7	d-limonene VOC injection without PCO air cleaner operating	140 – 5.8
8	d-limonene VOC injection with PCO air cleaner A operating	120 – 5.0
9	d-limonene VOC injection with PCO air cleaner B operating	140 – 5.8

5.4 Experimental conditions of the research houses during testing

This section specifies the influential factors relevant to the experimental conditions of each test. Each room in test house 2 has a ceiling fan and at least one supply and return register. Since the testing will consider the VOC concentration of the whole home, all ceiling fans in the house were powered on in addition to the HVAC system being powered on to allow for good air mixing within the test house. All interior doors were left open in contrast to all exterior doors remaining shut throughout each experiment. In terms of the thermoregulation of the house, the HVAC was set on 99 °F in cooling mode to ensure that the compressor would not be powered on during testing. In preliminary VOC monitoring of the test house, it was seen that the powering on of the compressor would lead to unwanted spikes in VOC readings which were affected by climatic variables. Therefore, the temperature and humidity in the house was dependent on the climate outdoors. The initial temperature and humidity values were recorded for each experiment and are presented in *5.7.1 Comparison of natural decays to decays under the operation of a PCO*. It is also important to note that the 24-hour period allocated for the calibration of the AWAIR sensors (*see Appendix C)* is also regarded as the ventilation in between VOC experiments.

5.5 Specifications of tested PCO air cleaners

As stated in *5.3 Experimental methods for VOC injection*, the two PCO air cleaners included a frame, a filter, and the PCO core itself. The PCO cores differed in size and light intensity with PCO air cleaner A's core being bigger than PCO air cleaner B's. The specifications of the two PCO air cleaners are shown in Table 14. Both wavelengths were provided by the manufacturers of the PCO air cleaners. In the case of PCO A, the highest wavelength output of the bulb is given. In case the case of PCO B, a range in wavelength that PCO operates in was provided.

Table 14. Specifications of PCO A and B

Design Factor	**PCO A**	**PCO B**
Size (L x H x W in inches)	16.5 x 13.5 x 1	20 x 1.875 x 1
Lamp Type	Not specified	UVA
Lamp power (Watts)	96	55
Number of lamps	528 LEDs	1 lamp
UV wavelength (nm)	395	315-350
Attached filter (MERV)	Not specified (13)	Carbon filter (16)
Catalyst	Titanium dioxide	Titanium dioxide

The cores of the two PCO air cleaners, individually and in the plenum, are shown in Figures 31 and 32.

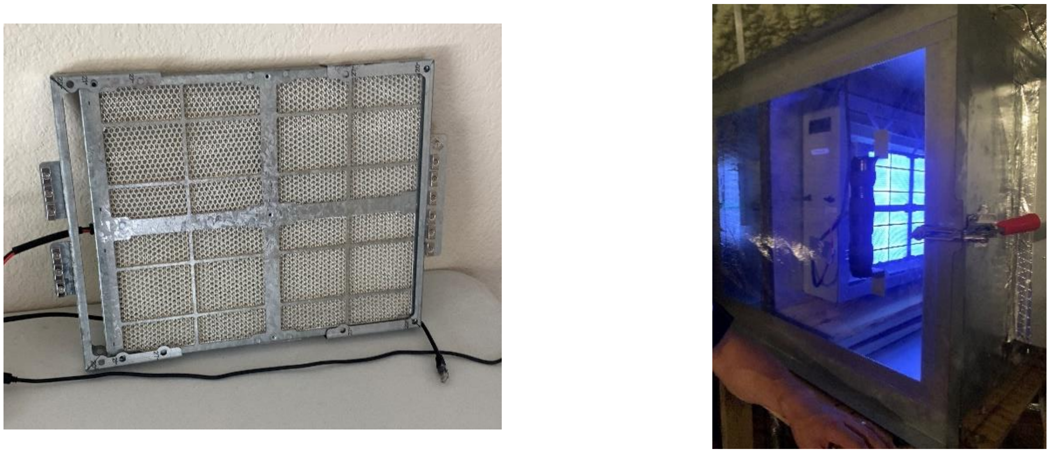


Figure 31. PCO A core (left) and in plenum (right)

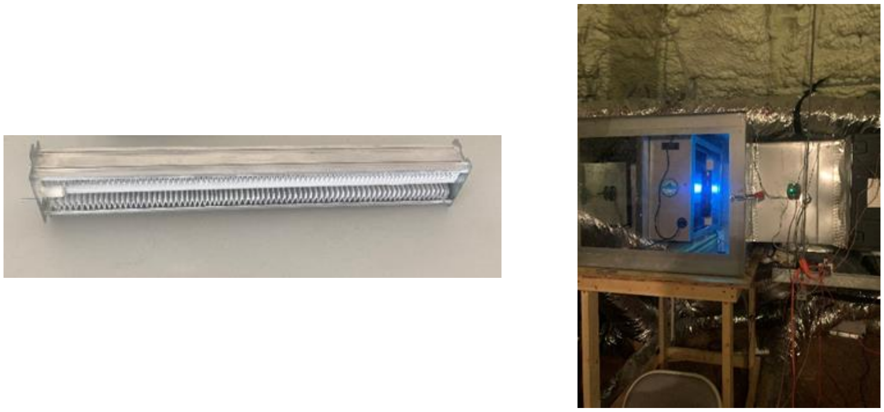


Figure 32. PCO B core (left) and in plenum (right)

5.6 Evaluation of PCO air cleaner methodology

In review of fan-driven air cleaning technologies, Zhang et al. [40] were tasked with comparing the results of different single-pass tests and chamber tests related to PCO air cleaners. They go on to state that, "the performance of air cleaners is best measured and compared with the use of Clean Air Delivery Rate (CADR)." CADR is the product of the single-pass removal efficiency and the volumetric flowrate going through the air cleaner. According to the ASHRAE journal, CADR can also be calculated using Equation (5), where V is the volume of the test space and $\left(L_{on} - L_{off}\right)$ is the difference between the first order loss rates (hr^{-1} or min^{-1}) for periods when the PCO air cleaner was powered on and off respectively [62]. Since each VOC experiment was represented by a double exponential function, the curve fits can be linearized by taking the natural logarithm of those curve fits. These linearized logarithmic functions can then be represented as linear functions ($y = mx + b$), where the slopes (m) can then be used as the corresponding first order loss rates (L).

$$CADR = V\left(L_{on} - L_{off}\right) \qquad \text{Equation (5)}$$

5.7 Results and discussion of VOC experiments

5.7.1 Comparison of natural decays to decays under the operation of a PCO

Even though variations in temperature and humidity (based on diurnal cycles of indoor VOC concentrations) were removed using the correction model, there are differences in initial values of temperature and humidity that will be a factor in the characterization of each VOC decay related to seasonal effects in VOC concentration. Thus, leading to the different characterization of each VOC decay. Higher temperatures lead to an increase in VOC emission and diffusion rates concurrently with higher levels of humidity that lead to decreased levels of adsorption affecting decay rates seen in each VOC experiments [63]. In order to consider the effects of temperature and humidity on VOC decay rates, the initial values of temperature and humidity for each VOC experiment are listed in Table 15 (provided in the order that the experiments were conducted).

Table 15. Initial temperature and humidity values for all VOC experiments

VOC	**PCO status**	**Initial temperature** (°F)	**Initial humidity ratio** $\left(\frac{lb_w}{lb_{da}}\right)$
Paint	PCO OFF	82	0.013
	PCO ON: A	87	0.017
	PCO ON: B	86	0.012
Mr. Clean all-purpose cleaner	PCO ON: B	83	0.011
	PCO ON: A	83	0.012
	PCO OFF	82	0.013
d-limonene	PCO ON: A	77	0.01
	PCO OFF	79	0.012
	PCO ON: B	66	0.005

In this section, Figures 33 – 35 show the direct comparison of the exponential decays representing the different VOCs used to evaluate the PCO air cleaners. The time domain of the plots was selected based on the VOC experiment that had the smallest duration to focus on their performance at the same time instances, respectively. Each decay begins at the point at which the whole home VOC concentration was at or near the desired level. Table 16 shows the initial VOC concentration of each experiment.

Table 16. Initial VOC concentrations for all VOC experiments

VOC (Desired concentration)	**PCO status**	**Initial VOC concentration** (ppb)
Paint (4,000 ppb)	PCO OFF	4,224
	PCO ON: A	4,085
	PCO ON: B	4,125
Mr. Clean all-purpose cleaner (1,000 ppb)	PCO ON: B	918
	PCO ON: A	870
	PCO OFF	804
d-limonene (2,000 ppb)	PCO ON: A	1,964
	PCO OFF	2,118
	PCO ON: B	2,133

The paint VOC experimental results are shown and compared in Figure 33. It is worth mentioning that there are certain characteristics of the paint VOCs that will give insight into the decays seen that are explained in this section. Even though the house was ventilated for 24 hours in-between experiments, certain characteristics of the paint VOCs allowed them to accumulate in the house from experiment to experiment over time. The fact that the paint is oil-based means that it has low-water solubility which limits its adsorption onto water-droplets present indoors, increasing its ability to persist in the air [64]. Another reason for their persistence could be through the adsorption of the paint VOCs on indoor materials which can later be desorbed back into the space. This also leads into the reasoning for heightened levels of VOCs seen at the end of the decays. The baseline concentration of VOCs in the house varied in between 300 and 400 ppb, yet the concentrations seen at the end were significantly higher even with the powering on of the

PCOs. As mentioned in the *Introduction*, it is also possible that there could be some formation of VOC by-products from the PCO. However, without a direct comparison between the air immediately entering and leaving the PCO, it is hard to distinguish whether VOC by-products or the characteristics of the paint VOCs led to the heightened steady-state levels.

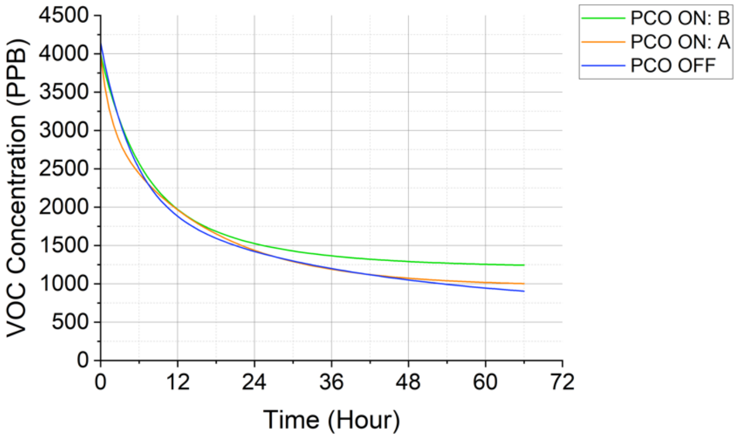


Figure 33. VOC decay comparison during paint VOC injection experiment

The Mr. Clean all-purpose VOC experiment results are shown and compared in Figure 34. It seems that as the experiments moved away from the paint experiments conducted first, the steady-state concentrations at the end of the decays decreased along with further ventilation of the house from experiment to experiment. The VOCs from the all-purpose cleaners were much less persistent in the air and less able to evaporate into the house to reach desired VOC concentrations (< 1,000 ppb). It seems that decays of PCO B and A were affected, respectively in order of relevance, by the VOCs leftover from the paint experiments conducted first. No major differences in initial temperature and humidity were seen in the all-purpose cleaner VOC experiments with standard deviations of ($\pm$ 0.5 °F) and $\left(\pm 0.001 \frac{lb_w}{lb_{da}}\right)$, respectively.

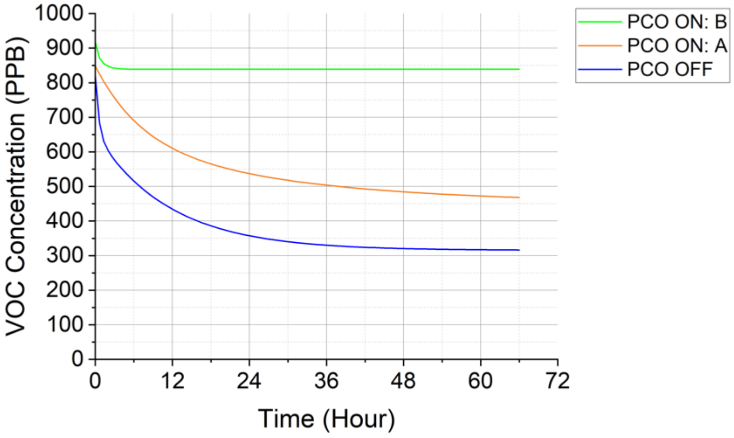


Figure 34. VOC decay comparison during Mr. Clean all-purpose VOC injection experiment

This, however, was not the case for the d-limonene VOC experiments, shown in Figure 35. The steady-state concentrations seen at the end of the decays were closer to the household baseline VOC average which seems to be due to the lower temperatures seen in the experiment. The highest drop in initial temperature and humidity was seen in the PCO ON: B period of the d-limonene test which looks to have played a factor in why the concentration reached a low steady-state. Quantitatively, the increase in the standard deviation of temperature $(\pm 5.7\ °\mathrm{F})$ and humidity $\left(\pm 0.003 \frac{lb_w}{lb_{da}}\right)$ from the Mr. Clean illustrates the previous point.

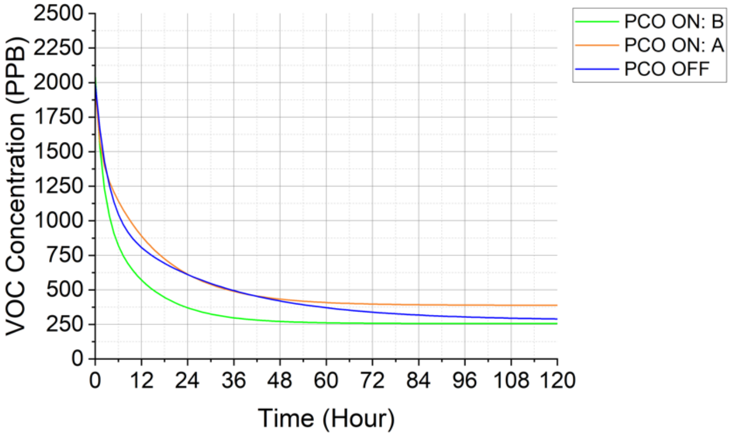


Figure 35. VOC decay comparison during d-limonene VOC injection experiment

Referring back to the paint VOC experiments, keeping in mind that the accuracy of the VOC sensor readings is 15%, there is no visible acceleration of VOC abatement that is seen in the exponential plots due to the powering on of either of the two PCOs. The main differences seen are the differences in steady-state concentrations seen at the end of the decays. In the Mr. Clean all-purpose cleaner VOC experiments, neither of the decays during the powering on of the VOC were lower than the natural decay of VOCs with no PCO powered on. Rather they were significantly higher. As discussed earlier, this could be the result of remnant paint VOCs from the previous experiments oversaturating the PCO reaction surface giving a higher load on the Mr. Clean all-purpose cleaner experiments done first than the latter ones. A factor of which would also affect the periods in which the PCOs were allowed to regenerate (mentioned in *5.3 Experimental method for VOC injection*) leading to the reduction of PCO capabilities. It should be noted that the influence of humidity in the Mr. Clean all-purpose cleaner experiments was minimal and would not cause the major differences in the steady-state concentrations that the curves settled at. The average temperature (81.47 °F), absolute humidity (72.73 grains/lb), and relative humidity (RH) (45.3%) seen throughout the Mr. Clean experiments had standard deviations of 0.12 °F, 2.34 grains/lb, and 1.27 %, respectively. Lastly, with regards to the d-limonene VOC experiments, no significant difference is seen between the powering on of PCO A and the PCO OFF, with the exception of the PCO ON: B in the initial decay. However, due to the initial temperature and humidity in the PCO ON: B period being noticeably lower than the others, the quicker decay cannot be solely attributed to PCO B.

Figures 36-38 show the linearized decays of the VOC experiments. As mentioned in *5.6 Evaluation of PCO air cleaner methodology,* the decay curves (seen in the previous section) are linearized by taking the natural logarithm of each curve. The linearized curves are then characterized by a linear function $(y = mx + b)$, where the slopes (m) from each function are taken as the first order decay rates that are needed and used to calculate CADR in the section *5.7.2 Evaluation of PCO performance*.

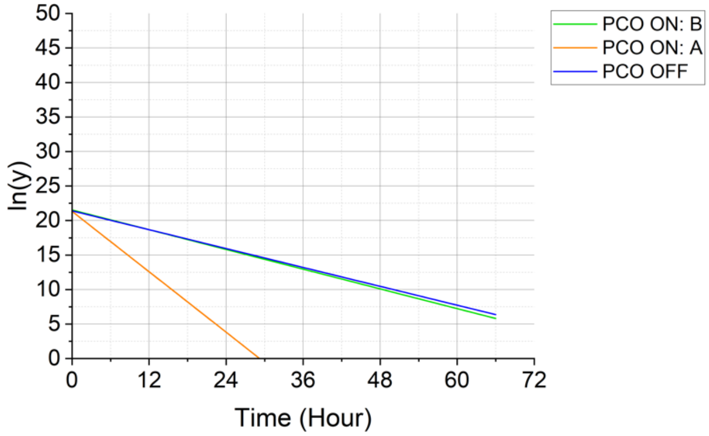


Figure 36. VOC linearized decay comparison during paint VOC injection experiment

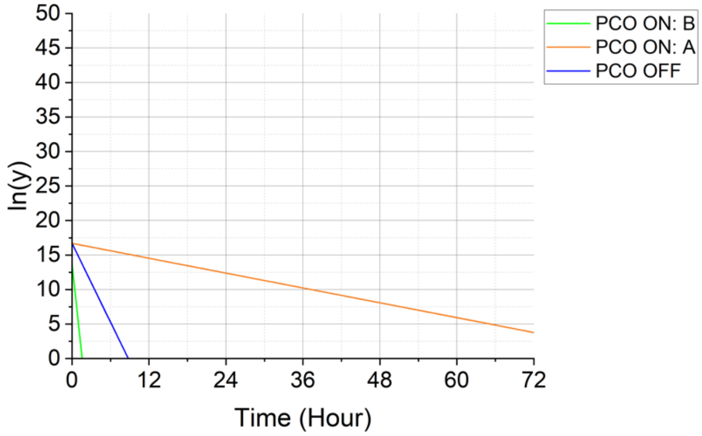


Figure 37. VOC linearized decay comparison during Mr. Clean all-purpose VOC injection experiment

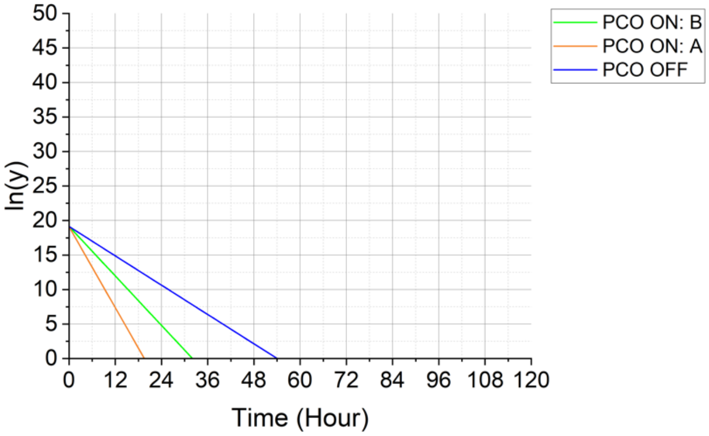


Figure 38. VOC linearized decay comparison during d-limonene VOC injection experiment

The total slope (*m*), that characterizes the linearized double exponential decay, is the sum of both decay rates in the original double-exponential decay curves. In other words, the total slope is the summation of *b* and *d* from Equation (3) in *4.3 Methodology for VOC correction model*. The total slope will be dominated by one of the two decay rates if one is considerably larger than the other. In the case of the paint and d-limonene, as seen in Figures 36 and 38, the decay slopes for the PCO ON periods are larger than the PCO OFF period, which would indicate some level of acceleration of VOC abatement. However, this is not the case for the Mr. Clean VOC experiment. It seems that the total slope for the decays of the PCOs in the Mr. Clean VOC experiments are being dominated by the larger secondary decay rate because they reach higher steady states more rapidly. For this reason, only the first decay rates (*b*) will be used in calculating their CADR to try to minimize the effect of the significant differences between steady-state concentrations.

5.7.2 Evaluation of PCO performance

In order to provide quantitative differences in between VOC experimental periods, CADR and single-pass removal efficiency are provided. This will also allow for a comparison to be made between the PCOs tested in this thesis study and others reported in literature. It must be mentioned that CADR is primarily used in closed and controlled chamber testing therefore the effects of initial temperature and humidity, and infiltrations should be considered. Table 17 gives the CADR and single-pass efficiencies for both PCOs. The single-pass efficiency is computed, as explained in *5.6 Evaluation of PCO air cleaner methodology*, by dividing the CADR with the volumetric flowrate going through the PCO (803 CFM) when the fan is powered on at 100% (according to the diagnostic portal of the HVAS system as stated in 3.3 Overview of ozone experiments).

Table 17. CADR and Single-Pass Removal Efficiency of PCO A and B

VOC	**PCO**	**CADR (CFM)**	**Single-Pass Removal Efficiency (%)**
Paint	A	100	12.4
	B	2	0.3
Mr. Clean all-purpose cleaner	A	-343	-42.8
	B	-180	-22.4
d-limonene	A	124	15.4
	B	48	6

The single-pass efficiency in Table 17 shows the ability or inability of the PCO device to accelerate the decay rate of the spike in VOCs injected into the test house. A positive single-pass efficiency in the table would indicate an acceleration in VOC abatement, while a negative value would indicate a deacceleration. For the paint and d-limonene VOCs, PCO A was found to have the higher single-pass removal efficiency than PCO B, considering differences in initial temperature and humidity, and residual VOCs. This distinction is representative of differences in design factors of the two PCO air cleaners, as described in *5.5 Specifications of test PCO air cleaners*. When oxidizing VOCs, PCOs with UV wavelengths closer to 315 nm would require less time for reaction due to a higher photon energy level [65]. While the PCO B would produce UV irradiance that would be more "efficient" in oxidizing VOCs, the PCO A has a bigger surface area for reactions to take place in addition to a higher number of UV lamps leading to a higher level of irradiance increasing the rate of photovoltaic reactions. These factors, confirmed by the test results, would lead to PCO A having a design more suitable for higher removal efficiencies. A higher level of irradiance leading to a higher removal efficiency is an observation also seen in Zhong et al.'s [36] testing of in-duct PCOs (*2.2.2 Laboratory testing of PCO air cleaners)* where gradual increases in VOC removal efficiency were observed due to increases in irradiance intensity.

According to the literature, PCO CADR and removal efficiencies vary significantly based on the scale of the experiment, experimental design, PCOs tested, and the injected VOCs. Referring back to the systematic evaluation of in-duct PCOs performed by Zhang et al. [36], mentioned in the *2.2.2 Laboratory testing of PCO air cleaners*, three difference types of PCO setups (in combination with filters) were evaluated using 8 different pure-VOCs. The positive single-pass removal efficiencies ranged from 3 to 40%. It is important to note that the PCOs evaluated in the study were exposed to a mixture of VOCs as opposed to laboratory studies with singular VOCs, which is more representative of a real indoor environment. A factor which played a role in how the different VOCs reacted on the surface of the photocatalyst.

Also mentioned in *section 2.2.2,* through Shayegan et al.'s [41] testing of PCO air cleaners in different scaled experiments, was how the removal efficiencies of VOCs decreased as experimental conditions became more representative of real-world conditions. Thus, being the reasoning for low removal efficiencies seen in this thesis study in comparison to higher removal efficiencies seen in laboratory experiments. With respect to the values seen in the Mr. Clean all-purpose cleaner experiments, it would imply that the PCOs are actually worsening indoor air conditions as opposed to improving them. Rather, as discussed throughout the paper, the VOCs leftover from the previous paint VOC experiments led to the oversaturation of the PCO photocatalysts and an increase in the steady-state levels of VOC concentration in the test house during the PCO ON periods. Thus, not painting an accurate picture of the performance of the two PCOs.

Considering the 15% uncertainty of the VOC sensor readings, differences in initial temperature and humidity, and the accumulation of certain VOCs from experiment to experiment, the single-pass removal efficiencies of the PCOs are not high enough to suggest real effectiveness in the acceleration of VOC abatement. An observation clearly seen in the decay plots of the different testing periods (PCO OFF and ON). Further reasoning on the factors related to the low removal efficiencies include the flow rate of the air passing through the PCO and the photocatalyst used. The high airflow rate seen in the test house led to significant reductions in the calculation of removal efficiency for the PCOs which stems from less residence time for the VOCs to react with the PCO. Also, apart from being oversaturated in the Mr. Clean all-purpose cleaner VOC experiments, the reactions from the PCOs and their photocatalysts were not enough in being able to show a significant acceleration in VOC abatement that could be seen in the exponential decay plots.

5.8 Conclusions from VOC experiments

When comparing the exponential decays of the experimental periods, no significant acceleration of VOC abatement was seen with the powering on of the PCO air cleaners. Clean Air Delivery Rate (CADR) was used to provide a quantitative value of the PCO’s effectiveness which was also be used in the computation of single-pass removal efficiency. In the paint and d-limonene paint VOC experiments, PCO A had higher removal efficiencies of 12.4 and 15.4%, respectively. The removal efficiencies of the Mr. Clean all-purpose cleaner VOC experiments were not considered due to significant differences in the steady-state concentrations seen in the test home. Different factors, including PCO irradiance and surface area of reaction, led to PCO A having higher removal rates than PCO B. Keeping in mind differences in initial temperature and humidity, residual VOCs from previous experiments, and the 15% uncertainty of the sensor, the removal efficiencies from either of the PCOs are not enough to suggest high VOC abatement effectiveness in the home.

It must be noted that there are findings from the VOC experiments related to experimental design that can be improved and considered to aid the future real-world testing of PCO air cleaners. First is the spacing and order of VOCs experiments. To remove the effects of residual VOCs bleeding back into the test environment from previous experiments, it is recommended that more time be given for the ventilation of the test space in between experiments (24 hours in this study). While determining an approximate time period of ventilation using the sorption properties of the VOCs and major materials in the house, the most feasible approach would be to observe the baselines before and after VOC injections. Another finding is the suggested order in VOCs injected. Products with VOCs that are considered less persistent should be tested last. Reconsidering the order of VOCs in the VOC experiments would have led to the Mr. Clean all-purpose cleaner being used first, the pure d-limonene being used second, and the paint being used last. This is in addition to a reconsideration on the regeneration procedure of the PCO catalyst. If the VOC experiments in this thesis were to be repeated, it would be recommended that the PCO be powered on during the 24-hour ventilation period of the test home to further reactivate the PCO catalyst.

The second finding is the use of the climatic correction model to remove variations in initial temperature and humidity. This was key in defining the decay curves for all the different VOC experiments and being able to compare them to each other. Overall, the most important factor that led to the decay curves being significantly different was the order of VOCs and time of ventilation in-between VOC experiments. A methodology to accurately compare VOC experiments that differ noticeably in initial temperature and humidity would also be beneficial in future PCO field testing. Overall, there are a lot of trends related to experimental design and results seen in the data that confirm previous experiments performed in the literature in addition to findings that address the real-world testing of PCOs.

CHAPTER 6 – CONCLUSIONS AND RECOMMENDATIONS

The improvement of poor IAQ in residential buildings requires an assessment of indoor contaminants present indoors, in addition to the selection or combination of different mitigation strategies. Such strategies include ventilation, the use of high efficiency filters, and air cleaners or air purifiers. Assessing the effectiveness of these mitigation strategies is important for the development of effective IAQ mitigation plans for residential buildings. Two air purification technologies that have been explored for their potential in improving indoor air quality were ES air cleaners and PCO air cleaners. There is limited literature on both technologies specifically measured at the breathing zone, which is the space considered for human occupancy. Furthermore, there is currently no literature regarding the evaluation of a PCO air cleaner in a whole home environment. The examination of two ES air cleaners and two PCO air cleaners in this thesis gives insight to the effectiveness or safety of these technologies in real-world applications.

The ES air cleaners used in this thesis were tested to determine the extent that they increased indoor concentration levels of ozone. Both ES air cleaners were found to increase indoor ozone levels in the test house; however, the extent to which they were increased was less than the FDA limit of indoor ozone (21CFR801). This was also the case when reviewing studies that observed the generation of ozone from in-duct ES air cleaners. Referring back to the thesis, it was also found that even in periods where the test house was mechanically ventilated that the indoor ozone levels never exceeded the FDA limit on indoor ozone. The results from the ozone experiments in this thesis provide distinct data more relevant to occupant exposure. The studies mentioned in the literature measured ozone concentrations downstream of the ES air cleaners as opposed to in-room in the thesis. The distinction of measuring ozone concentration levels in-room prevents the overestimating of ozone generation by focusing on the breathing zone. In conclusion, the findings from the ozone experiments provide more information regarding the safety of using ES air cleaners in residential applications.

Shifting focus, the PCO air cleaners used in the thesis were tested to determine their effectiveness in accelerating the abatement of indoor VOCs. After comparing the curves with and without PCO operation in addition to quantitative values for removal efficiency, there is no evidence to support effectiveness from the PCOs in accelerating the abatement of indoor VOCs. The highest removal efficiency seen in the literature review of PCO air cleaner testing was 72.1% for a chamber tested PCO air cleaner by Weon et al. [45]. The rest of the removal efficiencies seen in the literature review ranged from 0 to 70%. Noted, the removal efficiencies seen in the literature review were related to singular VOCs, not a collection of VOCs as seen in this thesis. The main takeaway from the VOC experiments performed in this thesis, in conjunction with the literature review of PCO testing, is that the use of PCO air cleaners in real-world residential applications are not ready for practical use. Further advancements need to be made in the development of photocatalysts that can effectively abate groups of VOCs at air flowrates representative of realistic conditions (i.e., air flowrates seen with AHU fans in residential applications). Nevertheless, additional findings from the VOC experiments presented in the thesis can assist the future real-world testing of PCO air cleaners. Including suggesting more ventilation time in-between experiments, the order of VOCs, and the development of the climatic correction model. By using the correction model, variations in temperature and humidity that caused unrelated changes in VOC sensor readings were significantly reduced, allowing for a comparison of VOC decay with and without PCO operation.

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Appendix A – Ozone monitor zero check

To ensure the quality of the ozone monitor data, the ozone monitor was periodically zeroed out throughout the experiments. The zero check is performed by zeroing the ozone monitor around a reference point of zero ozone with the use of an ozone scrubber provided by the manufacturer (see Figure 39). The ozone scrubber is attached to the ozone monitor reading input (see Figure 40). The ozone monitor is then calibrated to read 0 ppb with the ozone scrubber on. The ozone scrubber is then removed to make readings, and the calibration is complete.

Figure 39. Ozone scrubber

Figure 40. Ozone scrubber attached to ozone monitor

Appendix B – Justification for the horizontal and vertical placement of the ozone monitor

The location of the ozone monitor was determined as the result of a stratification test and a test that measured the critical point of ozone in the test house. The ozone monitor was placed on a stool at the center of three bedrooms and set to read background indoor ozone levels. The results are shown in Table 18.

Table 18. Critical Point of ozone Test

Room	Ozone (ppb)
Master Bedroom	2.8
Bedroom 2	2.9
Bedroom 3	2.7

The room location of the ozone monitor seemed to minimally affect the ozone readings. For this reason, the sensor was placed in a centralized location in the house in the living room.

The stratification test measured ozone concentrations at different heights from the ground. The ozone monitor was raised in increments of 11.25 inches by being placed on ladder steps. The results are shown in Table 19.

Table 19. Stratification of ozone test

Height (Inches)	Ozone (ppb)
11.25	2.8
22.50	3.0
33.75	3.5
45.00	3.6
56.25	3.6
67.50	3.4

The critical point of ozone was around 45-56 inches from the ground. This is considered “waistline” level. For this reason, the ozone monitor was placed on a stool in that height range.

Appendix C – AWAIR sensor recalibration process

Technical information on the AWAIR IAQ sensors were obtained from online documents and direct conversation with the manufacturer. Based on the methodology of VOC testing in the study, the manufacturer recommended that the AWAIR sensors be manually reset every week or for every different test with different chemicals. In order to reset the multiple AWAIR sensors, they must be exposed to fresh air in the same room in order to have the same reference baseline. The AWAIR IAQ sensors were placed in the living room of the test house with open windows in addition to mechanical ventilation being powered on (see Figure 41). Exposed to fresh air, the AWAIR IAQ sensors read their lowest possible value of VOC concentration which is close to 20 ppb. At that point, the AWAIR Element sensors are reset through the AWAIR mobile phone application where the option is found. While the official calibration of the sensor took 2-3 hours, it was recommended by the manufacturer to keep the sensors exposed to fresh air for a total of 24 hours. Once the sensors were reset, a notification was given indicating that the sensors were calibrated. They were then placed in their designated rooms with the windows closed (after the initial 3-hour period) and the mechanical ventilation being powered off (after a 24-hour period).

Figure 41. Resetting of the AWAIR IAQ sensors in the living room/dining room area

Appendix D – Justification for horizontal and vertical placement of AWAIR IAQ sensors

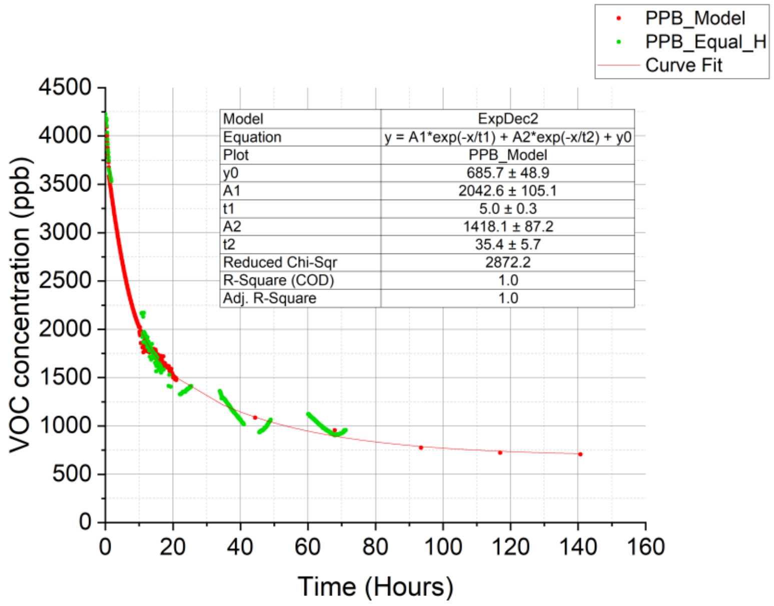
A study was conducted on the placement of VOC sensors for assessing Indoor Air Quality (IAQ). In the study, a simple model was developed to conclude how well different areas of a room correspond to the average VOC concentration of the occupied zone, given that occupants are the main source of VOC. Through literature review and the application of their model in two locations, an apartment and an office, some guidelines for the placement of sensors were developed. Some relevant guidelines from the study include [66]:

1. Sensors may be placed outside of the occupied zone, from a VOC perspective
2. VOC sensors should not be placed in corners, as particles tend to collect due to the no-slip principle and more stagnant air.
3. Particles collect in the ceiling, given the geometry and ventilation of the case studies, and the average concentration might be considerably higher there compared to other height averages
4. The best placement in theory is in the middle of the room, where none of the occupants touch or breath on the sensor, while VOC metering at walls may lead to spikes due to non-uniform behavior in particle concentration.
5. Measuring IAQ a few centimeters out from the wall or ceiling could result in values significantly closer to the average of the occupied zone

The EPA has similar guidelines for indoor IAQ sensor placement with the main suggestions being to install sensors out in the open, allow free air flow around sensor (at least 180 degrees), keep away from windows and doors, and to place near the typical breathing height (3 to 6ft) [67]. The guidelines and recommended actions listed above lead to the AWAIR Sensors being placed on chairs close to the 3 to 6 feet height range in centralized locations in their respective rooms.

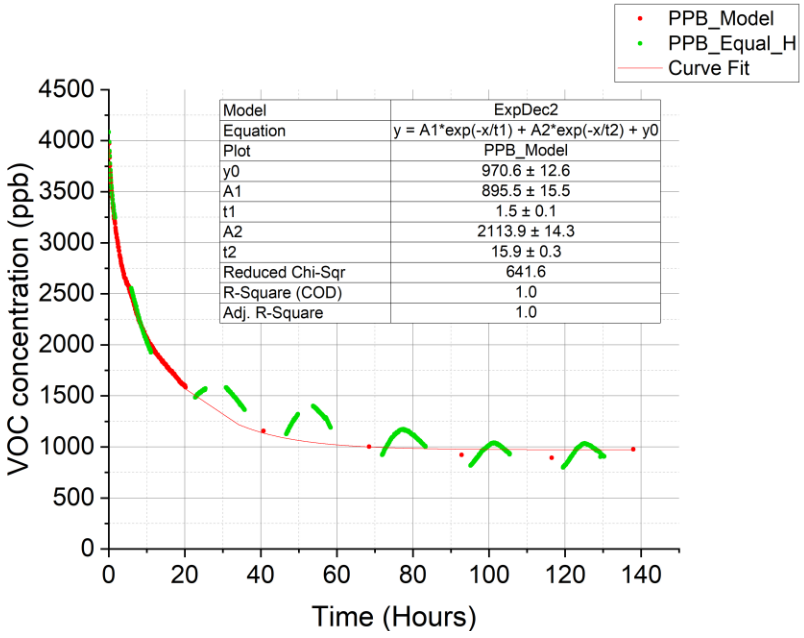
Appendix E – Verification plots for climatic correction model

Figures 42-50 show the results of decay fitting of the VOC injections experiments explained in *Correction model for climatic variables affecting VOC readings* presented in *Methodology and results for the evaluation of PCO effectiveness*.



Model	ExpDec2
Equation	y = A1*exp(-x/t1) + A2*exp(-x/t2) + y0
Plot	PPB_Model
y0	685.7 ± 48.9
A1	2042.6 ± 105.1
t1	5.0 ± 0.3
A2	1418.1 ± 87.2
t2	35.4 ± 5.7
Reduced Chi-Sqr	2872.2
R-Square (COD)	1.0
Adj. R-Square	1.0

Figure 42. Paint VOC injection – PCO OFF



Model	ExpDec2
Equation	y = A1*exp(-x/t1) + A2*exp(-x/t2) + y0
Plot	PPB_Model
y0	970.6 ± 12.6
A1	895.5 ± 15.5
t1	1.5 ± 0.1
A2	2113.9 ± 14.3
t2	15.9 ± 0.3
Reduced Chi-Sqr	641.6
R-Square (COD)	1.0
Adj. R-Square	1.0

Figure 43. Paint VOC injection – PCO ON – PCO A

Appendix E – Verification plots for climatic correction model (Continued)

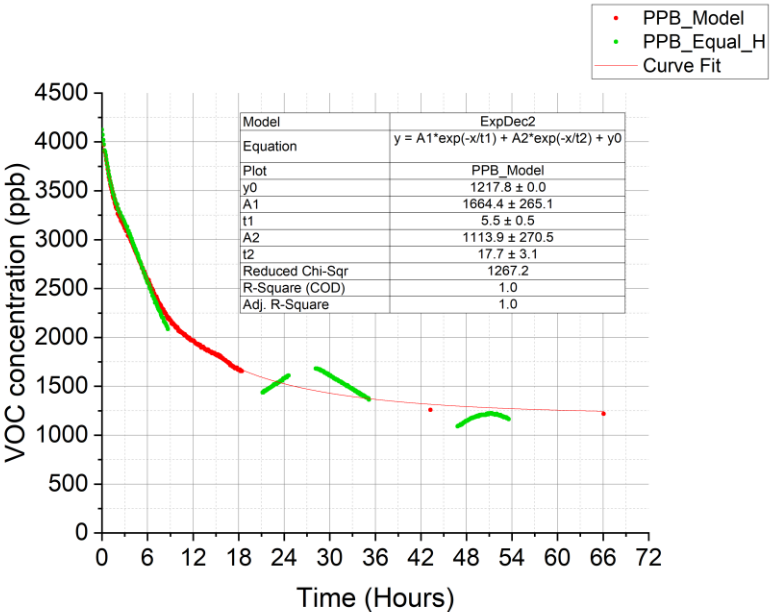


Figure 44. Paint VOC injection – PCO ON – PCO B

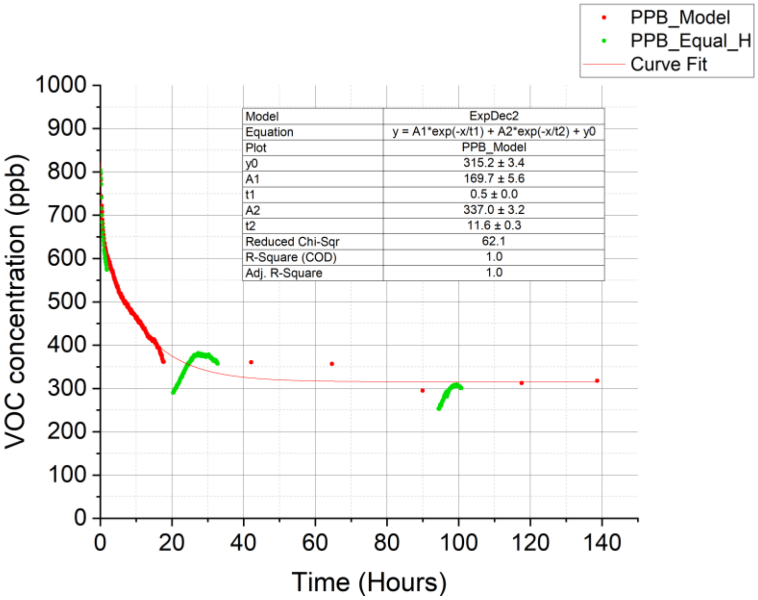


Figure 45. Mr. Clean all-purpose cleaner VOC injection – PCO OFF

Appendix E – Verification plots for climatic correction model (Continued)

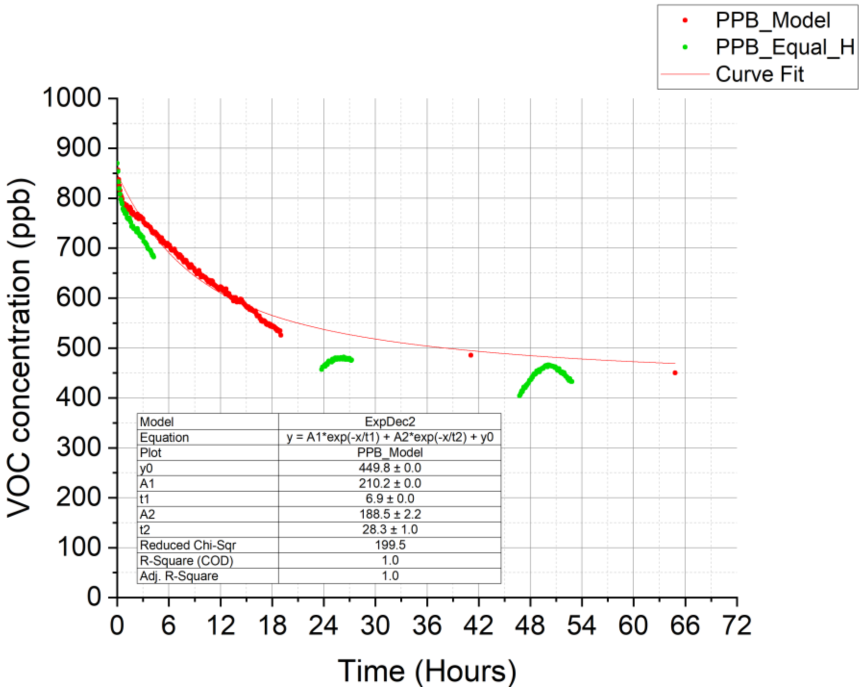


Figure 46. Mr. Clean all-purpose cleaner VOC injection – PCO ON – PCO A

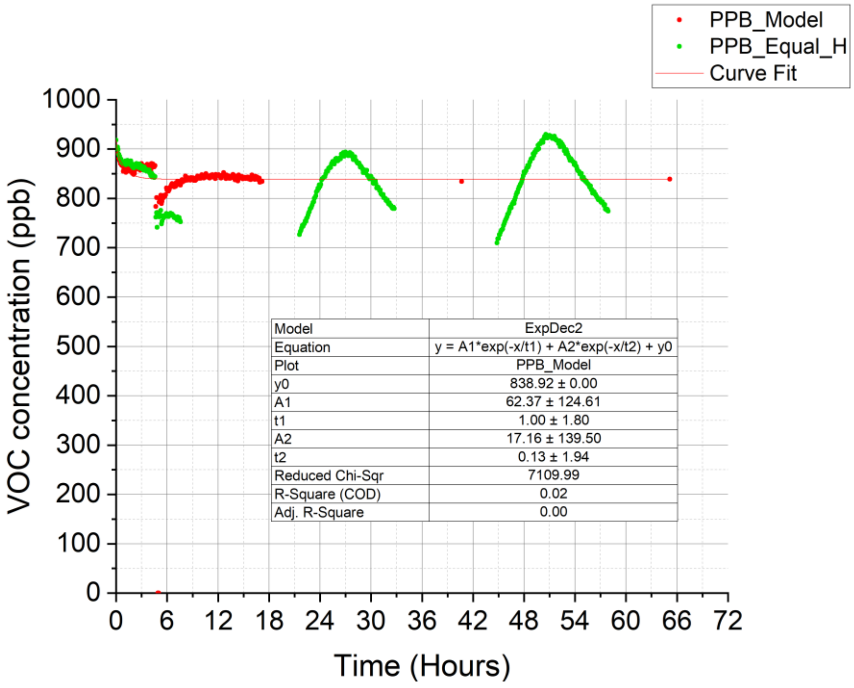
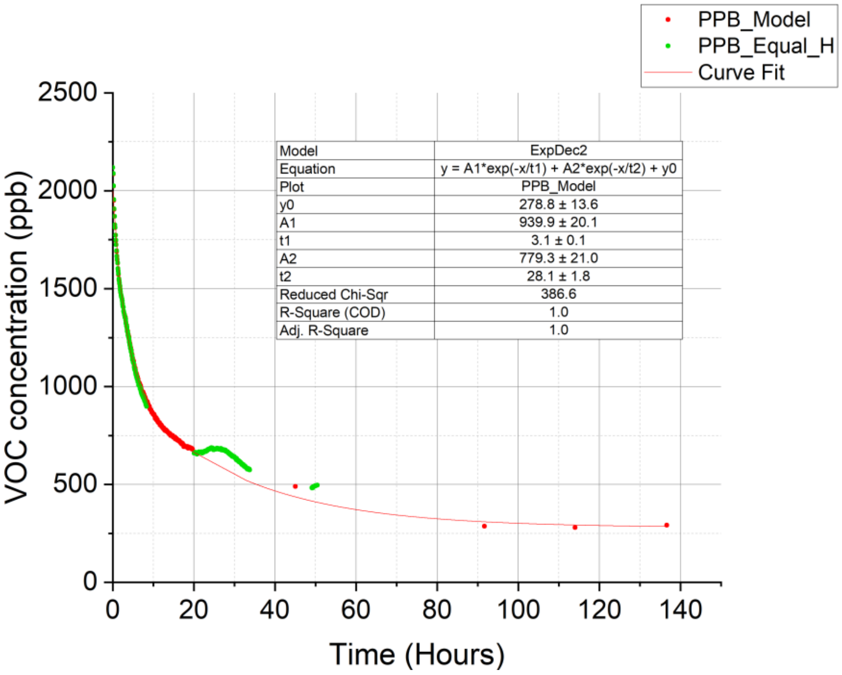


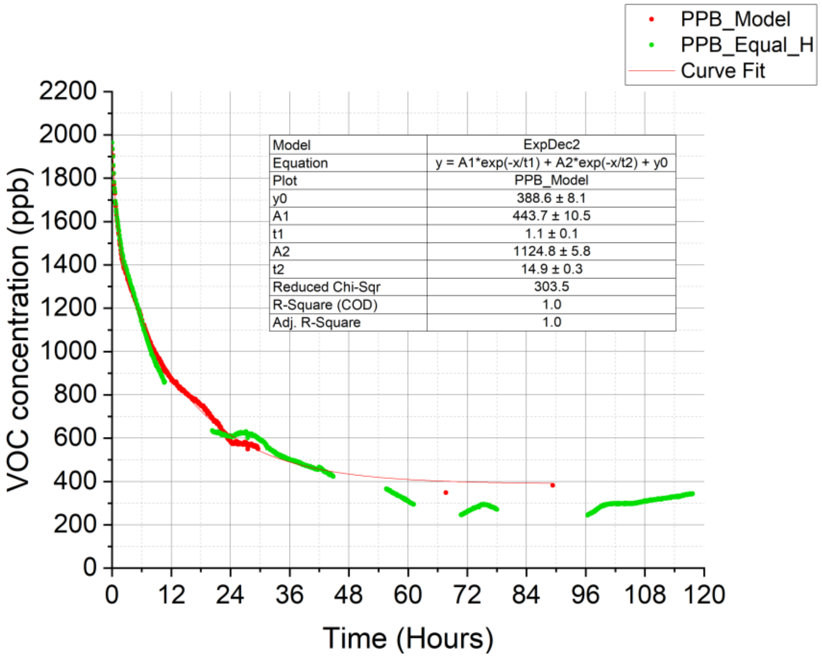
Figure 47. Mr. Clean all-purpose cleaner VOC injection – PCO ON – PCO B

Appendix E – Verification plots for climatic correction model (Continued)



Model	ExpDec2
Equation	y = A1*exp(-x/t1) + A2*exp(-x/t2) + y0
Plot	PPB_Model
y0	278.8 ± 13.6
A1	939.9 ± 20.1
t1	3.1 ± 0.1
A2	779.3 ± 21.0
t2	28.1 ± 1.8
Reduced Chi-Sqr	386.6
R-Square (COD)	1.0
Adj. R-Square	1.0

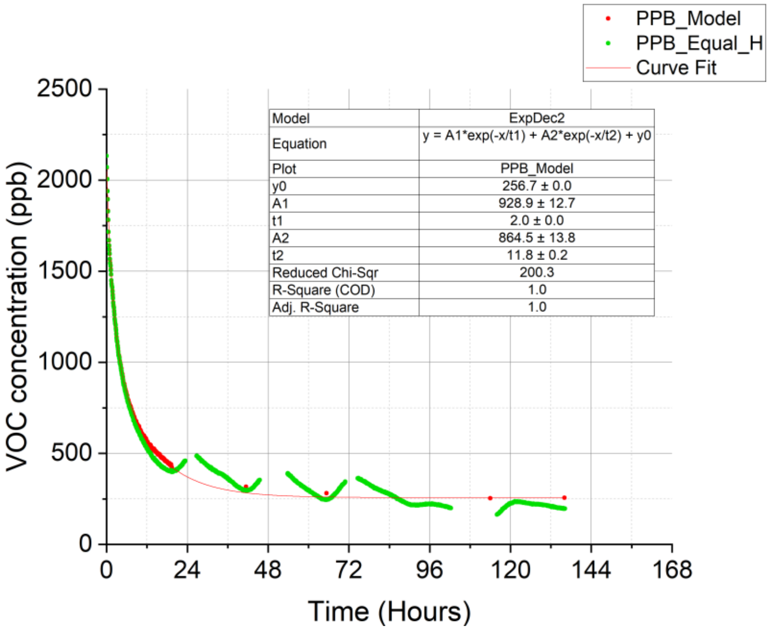
Figure 48. d-limonene VOC injection – PCO OFF



Model	ExpDec2
Equation	y = A1*exp(-x/t1) + A2*exp(-x/t2) + y0
Plot	PPB_Model
y0	388.6 ± 8.1
A1	443.7 ± 10.5
t1	1.1 ± 0.1
A2	1124.8 ± 5.8
t2	14.9 ± 0.3
Reduced Chi-Sqr	303.5
R-Square (COD)	1.0
Adj. R-Square	1.0

Figure 49. d-limonene VOC injection – PCO ON – PCO A

Appendix E – Verification plots for climatic correction model (Continued)



Model	ExpDec2
Equation	y = A1*exp(-x/t1) + A2*exp(-x/t2) + y0
Plot	PPB_Model
y0	256.7 ± 0.0
A1	928.9 ± 12.7
t1	2.0 ± 0.0
A2	864.5 ± 13.8
t2	11.8 ± 0.2
Reduced Chi-Sqr	200.3
R-Square (COD)	1.0
Adj. R-Square	1.0

Figure 50. d-limonene VOC injection – PCO ON – PCO B

Bio-sketch

Giovanni Cerrato was born in Palestine, Texas and has lived in east Texas for 23 years. He is a recent graduate from the University of Texas (UT) at Tyler. He graduated with a bachelor's degree in mechanical engineering and is seeking his master's degree in mechanical engineering at UT Tyler in the academic school year of 2022-2023. His main area of research is in the space of indoor air quality topics and technologies. His aim is to work in the HVAC industry.