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ABSTRACT

The novel Coronavirus disease (COVID-19) pandemic has driven innovation for the development of new air cleaning technologies with renewed interest in determining effectiveness of both new as well as existing cleaning technologies. Standardized test methods for the evaluation of reactive air-cleaning technologies for both volatile organic compounds (VOCs) and microbiological agents do not exist. Since air movement in a building is very dynamic and situational specific, the lack of standardized methods may lead to contradictory results or sub-optimal evaluation of a device's performance in a laboratory setting.

In this paper, a graphene enhanced photocatalytic oxidization (GPCO) device is presented and evaluated for general effectiveness against some challenge VOCs. The authors describe the VOC testing methodology used as well as variables that could impact the reproducibility and repeatability of the results. In addition, measurements of various by-products that could have been generated by the device, e.g., ozone, are presented. The results demonstrated that the tested device reduced concentrations of formaldehyde and toluene over time.

1. INTRODUCTION

The COVID-19 pandemic has spurred a growing body of research around indoor environmental quality (IEQ) factors, with added focus on indoor air quality (IAQ) due to the role it plays in mitigating the risk of transmission of certain airborne diseases. Indoor environmental quality is an occupant's perceived indoor experience of the built environment that includes aspects of thermal comfort, lighting, acoustics and IAQ. Standards to measure, maintain and optimize IEQ for energy consumption, thermal comfort, lighting, and acoustics are well defined, but standards for measuring IAQ are still under development at the time of this publication. IAQ contaminants of concern fall primarily into three classes: particles, gases (including volatile organic compounds, VOCs) and microorganisms. Distinct categorization of IAQ contaminants are not mutually exclusive and similar technology approaches can be used for mitigation. For example, both microorganisms and dust are particles whose total concentration can be reduced by particle removal technologies. IAQ standards to measure and optimize the quality of indoor air have been slow to develop in part because IAQ contaminants of concern are both difficult to control and measure within the built environment. One objective of this paper is to describe a testing methodology that could be used as input to develop a test standard to evaluate the performance of IAQ technologies against VOCs.

There are generally four traditional approaches to removing or reducing various IAQ contaminants. The first two approaches, dilution and exhaust, are usually used in combination to remove contaminants and reduce exposure to IAQ contaminants including particles, VOCs, and microorganisms. Increasing outdoor air ventilation to bring in more fresh air that has lower concentrations of IAQ contaminants will dilute or reduce the concentration of the contaminants in the occupied space. Increasing the supply of fresh air will also increase the exhaust airflow in order to maintain an adequate building pressure. Increasing exhaust airflow increases the rate at which the IAQ contaminants are removed from the occupied space. Dilution and exhaust are effective methodologies and are primary approaches in managing a building's IAQ through the HVAC systems. Of course, there are many building designs or environmental variables that have an impact on the IAQ contaminant removal or reduction effectiveness through the dilute and exhaust methodology; these will not be discussed here.

The third approach is to reduce the concentration of IAQ contaminants of concern through control of indoor humidity. HVACR systems are used to control humidity to improve indoor comfort. Generally, managing indoor humidity can support the mitigation of the growth of airborne and surface bound microorganisms like bacteria and fungi. ASHRAE® recommends 40%-60% relative humidity (RH) to maximize human comfort and to reduce microbial growth. Humidity can also have an impact on particle size and number of water-based aerosols of microorganisms after emission by a host source.

The fourth and last approach is passively cleaning the air through various means. One common approach is to capture the IAQ contaminant through filtration so it cannot reach occupants. Air is circulated through a filter and the contaminant can be captured through various mechanisms, but primarily through impingement or adsorption onto a filtration media. ASHRAE developed Standard 52.2 -2019, Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size, to determine the Minimum Efficiency Reporting Value (MERV) for air filters. This method is limited to media filters since it measures the pressure drop as particle loading of the filter increases. Devices, like electrostatic precipitators, which do not have increasing pressure drop with particle loading, cannot be given a MERV rating. Using a filter with a higher MERV rating is an effective tool in removing particles but may cause increased pressure drop in installations with little flexibility in filter choice. Increased pressure drop will increase energy consumption, but this increase in energy use can be more effective in reducing indoor contaminants than that associated with increased outdoor air ventilation or use of in-room air cleaners (Pistochini, 2021).

Another approach to cleaning is to break down or inactivate the IAQ contaminant in the air and/or on surfaces. For example, application-specific ultraviolet germicidal irradiation (UVGI) systems are now a widely accepted technology for controlling microorganisms and may be installed in the HVAC duct system or inside an HVAC unit to irradiate a surface like a coil or drain pan. Another approach that has been used as far back as the 1920s is to bring UVGI into the room (occupied spaces) and either treat a portion of the room's air as it circulates (e.g., upper room UVGI) or treat surfaces directly (typically unoccupied spaces). A wide range of additional air cleaning technologies have also been developed and are currently available on the market and the need for standard methods of testing these devices and verifying performance has become a clear priority. ASHRAE Standard 185.1 is a test standard available for assessing the single pass UV-C light efficacy toward bioaerosols but does not test the combination of the UV-C light in a specific air handler. ASHRAE Standard 185.2 is a standard developed for determining the efficacy of UV-C light irradiance of coils and duct surface inactivation. Standards have not been created for evaluating the efficacy of UVGI in-room inactivation. A safety standard exists for the generation of secondary contaminates such as ozone for air cleaning devices. ASHRAE Standards 62.1-2019, Ventilation for Acceptable Indoor Air Quality, requires that air-cleaning devices comply with UL 2998 which limits ozone to 5 parts per billion (ppb) or less (UL 2998, ED3). ASHRAE Standard 145.2 provides a test method for assessing the performance of gas-phase air cleaning devices, sorbent media, and gas/VOC-removing filters but applies to in-duct devices and media and not for in-room devices.

Recently, Trane Technologies accelerated the development and refinement of a set of HVAC-focused testing methodologies for measuring the safety (e.g., generation of by-products such as ozone), applicability, and efficacy of air cleaning devices and incorporated various facets from existing standards. Our approach was to develop methodologies and procedures that made sense within the framework of accepted test standards while considering the needs of air cleaners that are not yet covered by currently recognized test standards. Current test standards for in-duct devices only allow single-pass testing (ASHRAE 2017, ASHRAE 2016). For in-room air cleaners, AHAM AC-1 (2013), which gives the Clean Air Delivery Rate (CADR), measures reduction of particles but does not address gas-phase contaminants or duct mounted devices. The CADR for gas-phase contaminants can be determined experimentally during chamber experiments by measuring the decay kinetics of the contaminant in the presence (k_{observed}) and absence (i.e., natural decay, $k_{\text{observed, natural decay}}$) of the air cleaning device using the following equation (Ye 2021):

$$\text{CADR} = (k_{\text{observed}} - k_{\text{observed, natural decay}}) \times \text{Chamber Volume} \quad \text{(Equation 1)}$$

More specifically, the CADR is the amount of clean air the air cleaner produces such that a 100 cfm airflow device at 75% single-pass efficiency has a CADR of 75 cfm. Importantly, the chamber decay methodology of AHAM AC-1 allows longer exposure and multiple passes through the air cleaner. Thus, this method serves as the basis of the chamber work discussed here. We use the term CADR in this paper in the sense it is often used colloquially to mean a clean air delivery level but not to indicate the values are from an AC-1 test as is apparent from the descriptions of the testing.

One technology that showed promising efficacy towards VOCs was graphene-enhanced photocatalytic oxidation (GPCO), which employs a composite of graphene with the ubiquitous photocatalyst, titanium dioxide (TiO_2). Photocatalytic oxidation (PCO) has been studied for several decades and its application towards the cleaning of air streams remains a maturing technology (Jacoby, 1996; Tsang, 2019, Noguchi, 1998; Kormann, 1988; Schneider, 2014; Perry, 2011). The most widely used photocatalytic material in PCOs is TiO_2 which has a bandgap of 3.2 eV (corresponding to 388 nm). Bandgap excitation produces both a potent oxidizing agent (i.e., a conduction band hole) and a potent reducing agent (i.e., a conduction band electron), both of which lead to the formation of reactive oxygen species such as hydroxyl radicals ($^{\cdot}OH$), superoxide ($O_2^{\cdot-}$), hydroperoxide radical ($^{\cdot}OOH$), and hydrogen peroxide (H_2O_2) (Howe, 1987; Nosaka, 2017). A review of the literature shows that the following elementary mechanistic steps are the likely key contributors toward the production of reactive oxygen species (ROS) that can cause the subsequent degradation/oxidation of organic species like VOCs: (1) oxidation of surface-bound water molecules to produce hydroxyl radicals, (2) reduction of oxygen by conduction band electrons to produce superoxide followed by hydrogen peroxide, and (3) production of hydrogen peroxide from two adjacent surface-bound hydroxyl radicals (Howe, 1987; Nosaka, 2017; Schneider, 2014; Ishibashi, 1998). The ROS that are formed on the surface of TiO_2 during photocatalysis are often depicted as remaining on the surface until they decay or are utilized in the surface-based oxidation of incoming or nearby organic species Competing with ROS creation is the recombination of the conduction band electrons with valence band holes. This process diminishes the overall yield of ROS that can be created by absorbed photons. The quantum yield for producing ROS by TiO_2 and is reported to fall in the range 1-5% (Nosaka, 2017).

The GPCO device (Figure 1) comprises a photocatalytic structure that combines graphene with TiO_2. The composite photocatalyst becomes activated by nearby 390-395 nm UV-A light-emitting diodes which excites electrons across the bandgap of TiO_2 (ThermoKing 2021). In the transit bus application, the in-duct GPCO device is placed upstream from the HVAC unit to allow for cleaning of the airstream (Figure 1). Importantly, the GPCO device exhibits very low pressure drop.

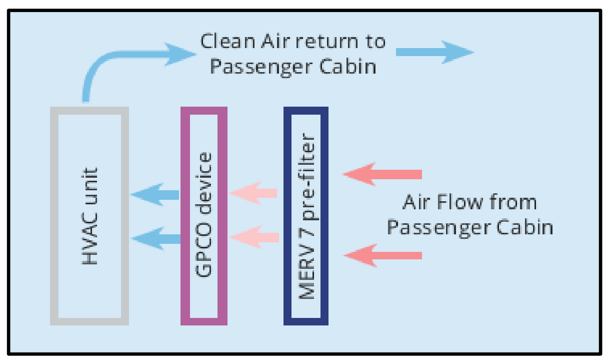

Figure 1. ***Left.*** Image of the Graphene-Enhanced PCO device used in bus applications. ***Right.*** In-duct placement of the Graphene-Enhanced PCO device in the bus application air flow.

The combination of TiO_2 with graphene is expected to have several implications on the resulting photocatalytic performance (Ng, 2010). For example, graphene offers an extremely high specific surface area (typically > 1000 m^2/g). As a carbon-based support with high surface area, this could facilitate the adsorption of gases like VOCs adjacent to TiO_2 photocatalysts that are then available and within the ROS generation field to allow for facile oxidation. The graphene could also play a role in improving charge separation and ROS yields by diminishing the rate of charge recombination (Ng, 2010). Given the potential that graphene could enhance the performance of PCOs, a series of experiments were performed to investigate the performance of the GPCO technology.

In this paper, emphasis will be made on the HVAC-focused testing methodologies that were developed for measuring the safety, applicability, and efficacy of the GPCO device toward select airborne VOCs. It should be noted that the GPCO devices were not manufactured by Trane Technologies.

2. EXPERIMENTAL

2.1 Test Chambers Overview

Many air cleaners require a longer period of time to operate and clean the air within a space; as a result, these air cleaners are not adequately covered by current standard test methods. Because of this, a test chamber similar to the AHAM AC-1 standard for testing in-room air cleaners for particle removal was a good starting point. However, some of these air cleaners are duct-mounted, so a simple chamber is not sufficient, and a combination chamber with a removable side duct apparatus was chosen as the basis for these tests. A removable side duct allowed the same chamber to be used for both in-room and duct-mounted devices. The two test chambers used for these experiments were 1007 ft^3 and 4096 ft^3 in volume, with both having an optional side duct with approximately 80 ft^3 of volume with an available 24"x24" device mounting section for mounting HVAC-mounted devices. Figure 2 provides an overview of the test chambers. Flexible 12-inch HVAC tubing was used to connect the side/by-pass duct with the chamber; for the 4096 ft^3 chamber, an additional ~30 ft of tubing was needed.

The individual sections of this side duct may be exchanged with other sections to provide more space, different access, or simply different sealing options. The smaller chamber size is equivalent to a typical office or bedroom and, as such, is quite appropriate for testing small-to-medium sized in-room air cleaners. It is not, however, the size that a full HVAC-mounted device would service. For example, a 2000 cubic foot per minute (cfm) unit would result in two air exchanges in 1 minute, or 120 air exchanges per hour (ACH) for this chamber, whereas in a real-world situation the same unit might serve 20 similarly sized rooms in a building, providing a more typical 6 ACH. The size of the chamber and of the duct as well as the intended airflow rate of the air cleaner must be considered when reviewing the test data. The chamber also allowed for air cleaners and sampling devices to be positioned in different locations. The internal fan could be run continuously to guarantee good mixing during the injection of contaminants to ensure good initial mixing. Alternatively, the internal fans could not be used at all to test a zero-to-low air flow condition. Three ceiling fans and two box fans at opposite ends of the chambers were used for both chambers. A variable frequency drive (VFD) was operated to adjust the test system blower to the desired test airflow rate in the by-pass recirculating duct. The chamber was purged with high-efficiency particulate air (HEPA) filters, carbon filters, and catalyst filters until stable baseline levels were reached. UV lights were also used to decontaminate the chamber after microbial tests. The

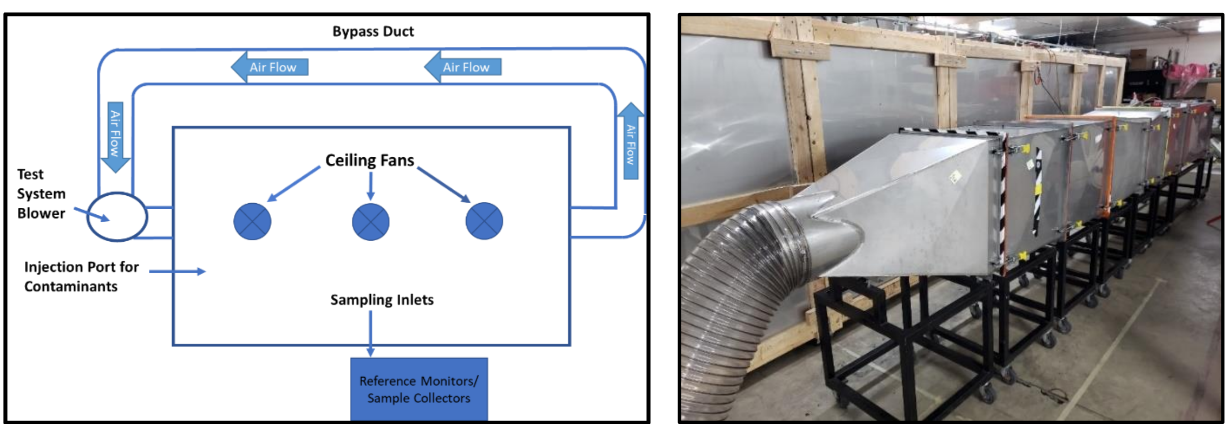

Figure 2. ***Left.*** Environmental test chamber schematic depicting placement of various sensors, injection location, and sampling locations. ***Right.*** Image of the chamber with the bypass recirculating duct.

purging processes lasted 30 to 60 minutes depending on the test contaminate and chamber size. Importantly, the experiments were carried out under closed chamber conditions (i.e., essentially zero outside air). Humidity was adjusted prior to the beginning of any tests to avoid the introduction of particles during the test.

2.2. Instrumentation

Multiple measurements were made during the environmental chamber experiments during each evaluation. Ozone was measured using an ACOEM Ecotech Serinus 10 Ozone Analyzer, with a measurement range of 0-20,000 ppb and a lower detection limit (LDL) of 0.5 ppb. Toluene was measured using a RAE Systems UltraRAE 3000 with a measurement range of 1 ppb – 10,000 parts per million (ppm). Background and generated formaldehyde were measured with an Aerodyne QC-TILDAS Formaldehyde Monitor with measurement range of 0-15 ppm. The potential for ions being produced by an air cleaner was monitored using an AlphaLab Air Ion Counter Model AIC2; two separate devices were used to measure positive and negative ions. Particle sizes and distributions over the size range 15-600 nanometers (nm) and concentration ranges of 1 to 10^7 particles/cm^3 were captured with a TSI Scanning Mobility Particle Sizer Spectrometer 3938. Temperature and relative humidity (RH) within the chamber were also monitored, using a TSI VelociCalc 9545, with typical ranges of 71-74ºF and 48-53%, respectively. Power consumption by the devices was also measured. When relevant, the airflow through an in-room device, due to its own fan, was determined, while for duct-mounted devices, the actual airflow rate through the duct was measured.

2.3 Introduction of Formaldehyde and Toluene into the Chamber

Aqueous formaldehyde (Ladd Research) was introduced into the test chamber using a custom-made flask evaporator with dry compressed air as the carrier gas. The toluene challenge was generated from anhydrous toluene (Sigma Aldrich). The analyzers for both formaldehyde and toluene were located outside the chamber. PTFE tubing was run from the inside the chamber to deliver air samples to the analyzers. Averages, changes over time, and changes relative to the timing of the experiment were calculated. For this report, the timescales were converted to time from the end of VOC injection and stabilization to the needed initial concentration to allow easier comparison across the tests. VOC injection times were typically 10-15 min.

2.4 Test Sequences (Induct versus In-Room Devices)

Two types of chamber decay tests, similar to AHAM AC-1, were derived using an environmental chamber, one for in-room devices and one for in-duct or duct-mounted devices. The GPCO devices were run for a certain length of time (typically several hours to overnight) prior to VOC challenge testing. This step was performed to ensure an activated state of the GPCO photocatalysts and removal of any residual organic compounds that may have been present on the photocatalytic surfaces.

In-Room Devices

1. Install air cleaner in the 1007 ft^3 or 4096 ft^3 chamber
2. Purge the chamber with ventilation system
3. Check for background levels of VOCs, ozone, particles
4. Inject VOC challenge into the chamber
5. Mix the chamber well with the fan
6. Collect air samples over time to determine the natural decay rate; measure other by-products such as ozone, ions, particles, and formaldehyde as needed.
7. Purge the chamber with the ventilation system
8. Repeat steps 2-7 but this time with the air cleaner on prior to or following the injection of the VOC
9. Calculate concentrations and decay rate.

In-Duct Devices

1. Set up the chamber with the bypass loop attached (1007 ft^3 or 4096 ft^3 chamber)
2. Install air cleaner in the bypass duct loop attached
3. Purge the chamber with ventilation system
4. Check for background levels of VOCs, ozone, particles
5. Turn on the air flow through the device and bypass loop
6. Inject VOC challenge into the chamber
7. Collect air samples over time to determine the natural decay rate; measure other by-products such as ozone, ions, particles, and formaldehyde as needed.
8. Purge the chamber with ventilation system
9. Repeat steps 3-8 but this time with the air cleaner on prior to or following the injection of the VOC
10. Calculate concentrations and decay rate.

3. RESULTS AND DISCUSSION

Organic chemical compounds are ubiquitous in both indoor and outdoor environments because they are essential ingredients in many products and materials and are generated by living and decomposing matter. In indoor environments, VOCs primarily come from the use and presence of products, materials, and objects (humans as well) which contain and emit VOCs into the air. The main concern in indoor environments is the potential for VOCs to adversely impact the health or comfort of people that are exposed to specific VOCs. The two target VOCs used in this evaluation were formaldehyde and toluene.

Formaldehyde exposure indoors is a problem in many parts of the world and is of concern in the United States (Kaden 2010). Formaldehyde is known to be difficult to generate, sample, and analyze. The Aerodyne QC-TILDAS formaldehyde monitor used in these tests provides the ability to selectively analyze for formaldehyde as both a challenge and a byproduct (either degradation product from larger molecule VOCs or off-gassing by the materials used within the air cleaner or chamber).

Toluene is one of the most commonly detected VOCs in indoor environments, along with benzene, ethanol, xylenes, and D-Limonene. In this study, toluene was chosen since it is the required challenge in ASHRAE 145.2 standard for the VOC category and because it requires multiple oxidative steps before it can be broken down into carbon dioxide (CO_2) and water. As such, this allows toluene to also be utilized to study potential breakdown byproducts for reactive air cleaners such as photocatalytic oxidation devices.

3.1 GPCO Performance Towards VOCs

The concentrations of specific VOCs (i.e., either formaldehyde or toluene) within the environmental chamber were measured as a function of time with and without the GPCO in operation. Plots of $\ln(C/C_o)$ versus time, where C_o is the initial concentration and C is the concentration at a given time point, were used to extract observed first order rate constants (in min^{-1}) for both the absence of the GPCO in the duct (i.e., natural decay) and GPCO device in the duct. These observed rate constants were used to calculate the CADR according to the following equation (Ye 2021):

$$CADR = (k_{observed,\ GPCO} - k_{observed,\ natural\ decay}) \times \text{Chamber Volume} \quad \text{(Equation 2)}$$

For all test cases involving formaldehyde, an initial concentration of 100 ppb was chosen, corresponding to 13% of the OSHA permissible exposure limit for formaldehyde in the workplace measured as an 8-hour time averaged value. Figure 3a provides representative data observed for a formaldehyde challenge test that is representative of air flows and air exchange rates for a residential or commercial building. In this instance, the CADR was determined to be 41 CFM which corresponds to the amount of clean air that the device delivers per minute. Table 1 summarizes the data collected for formaldehyde and provides data for both 1007 and 4096 ft^3 sized chambers as well as two different air exchange rates, specifically 6 and 20 ACH. All of the CADR data shown here falls within the range of 15 to 41. For the three cases of 101 CFM within a 1007 ft^3 chamber, the average CADR is 24 ± 15 CFM, demonstrating good reproducibility across different days of data collection.

Table 1. Summary of GPCO Performance toward Formaldehyde as a Function of Chamber Size and Air Flow

Chamber Size (ft^3)	Air Flow (CFM)	ACH	$k_{observed,\ GPCO} - k_{observed\ natural\ decay}$ /min^{-1}	CADR (CFM)
1007	101	6	4.1×10^{-2}	41
1007	101	6	1.5×10^{-2}	15
4096	410	6	9.0×10^{-3}	37
1007	101	6	1.6×10^{-2}	16
1007	336	20	3.4×10^{-2}	34

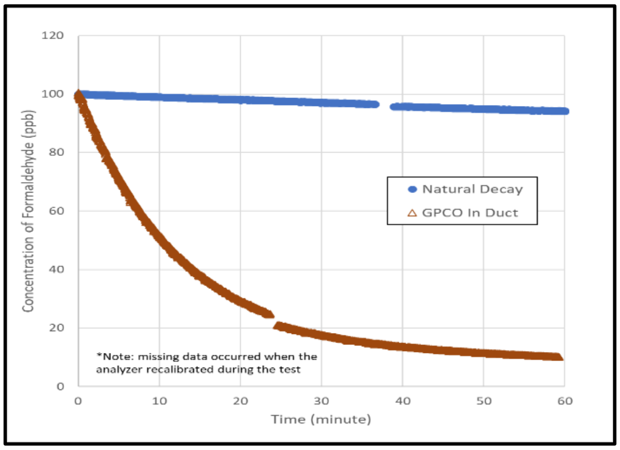

Figure 3a. GPCO performance towards formaldehyde when device is placed in-duct for a 1007 ft^3 chamber at 101 CFM (6 ACH).

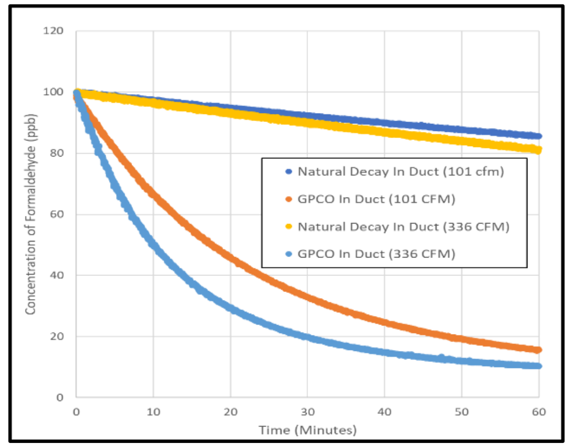

Figure 3b. GPCO performance towards formaldehyde when device is placed in-duct for a 1007 ft^3 chamber at 101 CFM (6 ACH) and 336 CFM (20 ACH).

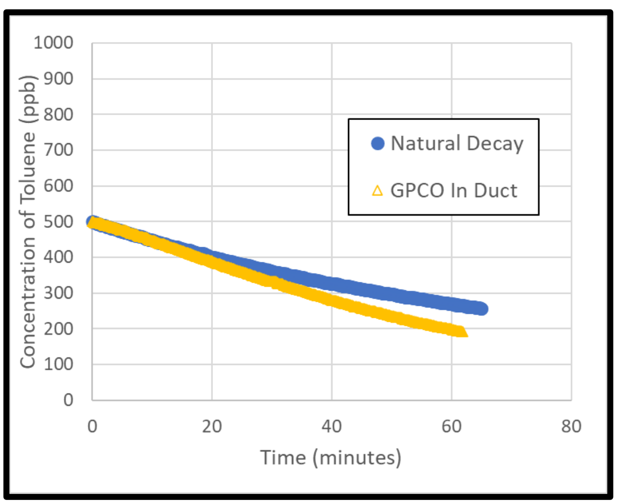

Figure 3c. GPCO performance (50 ACH) towards toluene when the device is placed in-duct for a 1007 ft^3 chamber

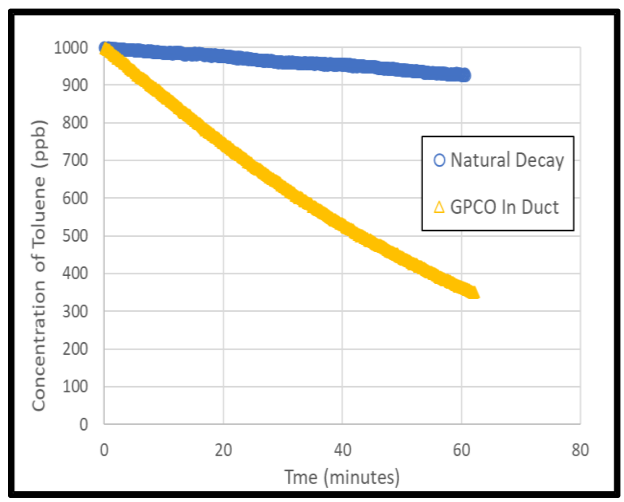

Figure 3d. GPCO performance (6 ACH) towards toluene when GPCO device with 254 nm light output is placed in-duct for a 1007 ft^3 chamber

Decay data was collected for toluene evaluations collected at two different air flows (101 and 840 CFM), corresponding to typical air exchange rates for a residential/commercial building and a bus application (6 and 50 ACH, respectively). Figure 3c shows the data taken at 840 CFM and 50 ACH to represent a typical bus application. The observed rate constants and CADR data collected for toluene are summarized in Table 2. Toluene decays were also compared at 101 CFM for two different initial toluene concentrations (not shown). As can be seen from the data, the CADR for the 50 ACH case increased by a factor of ~3 relative to the 6 ACH scenario. The higher air flow presumably increased the CADR by allowing more passes over the active photocatalyst. The CADR remained constant at both 500 and 1000 ppb initial toluene concentrations, which is consistent with these concentrations falling within the saturation regime of surface adsorption of toluene to the photocatalyst surfaces (Noguchi 1998).

The photoionization detector (PID) used to monitor the toluene concentrations does not differentiate between the different VOCs that are measured. As a result, both toluene and its breakdown products likely contributed to the signal. If this is the case, the kinetics of toluene removal may actually be faster than what is shown here. Data with speciation of the VOCs present is needed to understand this effect. To this end, proton transfer reactive mass spectrometry (PTRMS) will be used in future experiments to focus in on individual parent VOCs, as well as their byproducts (Ye 2021).

Table 2. Summary of GPCO Performance toward Toluene, 1007 ft^3 Chamber

Initial Toluene Concentration (ppb)	Air Flow (CFM)	ACH	$k_{observed, GPCO}$ /min^{-1}	$k_{observed, natural decay}$ /min^{-1}	CADR (CFM)
500	101	6	4.2×10^{-3}	2.0×10^{-3}	2.2
500	840	50	1.6×10^{-2}	1.0×10^{-2}	6.0
1000	101	6	4.6×10^{-3}	2.3×10^{-3}	2.3

In a different version of the GPCO device, the 390-395 nm UV-A lamps were replaced with UV-C lamps with 254 nm light output (Figure 3d). The utilization of higher energy photons resulted in a significant improvement in the decay kinetics of toluene corresponding to a CADR of 16 CFM. The larger CADR value may in part be due to a larger absorptance of 254 nm incident light by TiO_2 than in the case of the 390-395 nm LED.

3.2 Potential for By-Products Generation

Ozone is the byproduct that is most often mentioned for air cleaning devices because many electronic air cleaners, including both portable and duct-mounted devices, can generate high amounts of ozone. As a result, air cleaning devices, especially those sold in California, US, are tested to UL 867 and/or UL 2998 environmental standards to show low or no ozone produced. However, this test does not determine whether a device is functional, i.e., that the device neutralizes or inactivates contaminants, as claimed. A check of ozone during a contaminant removal test gives important information about the function of the device when it is working. Ozone was measured during the test sequence and the ozone levels measured during natural decay and during 60 min operation of the GPCO were both ~0.3-1.1 ppb, demonstrating that negligible ozone was generated by the air cleaner.

Ions outputs from air cleaners were measured systematically during our standard test methods because many technologies claim that ion production is an essential feature toward the achievement of high efficacies for microorganism inactivation. The ion counts were similar for both natural decay and VOC challenge tests remaining under 3000 ions/cm^3 for both.

Reactive air cleaning devices can form secondary organic aerosols (SOA) upon reaction with certain VOCs such as terpenes. In addition, certain air cleaning devices are intended to remove particles from the air by inducing particle agglomeration thereby creating larger particles that can more easily be captured by media filters. Thus, the concentration and sizes of the particles in the chamber are significant to understanding the performance of the device and by-products such as SOAs. During this study, cumulative particle counts of smaller particles in the 16-600 nm size range were measured using a Scanning Mobility Particle Sizer Spectrometer (SMPS). For toluene and formaldehyde, the particle concentrations measured during 60 minutes of operation of the GPCO device (~4000-12000 particles/cm^3) increased only slightly compared to natural decay (<2000 particles/cm^3) values, consistent with minimal SOA formation.

4. CONCLUSIONS

In this paper, we have introduced the HVAC-focused testing methodologies that Trane Technologies has recently adapted and developed for measuring the safety (i.e., generation of by-products), applicability, and efficacy of IAQ air cleaning technologies. We have focused here on the development and results of VOC challenge tests for a device based on GPCO and have focused on two VOCs, formaldehyde and toluene, commonly found in indoor spaces. The GPCO displayed a higher CADR for formaldehyde (CADR = 15-41 CFM) than for toluene (CADR = 2-6 CFM). This data is consistent with a slower photocatalytic process and breakdown for toluene, although the lower CADRs for toluene could be artificially low due to some limiting factors with the PID detector that was used since it cannot distinguish between specific VOCs. As a result, both toluene and its breakdown products likely contributed to the signal. In follow up studies, we will be overcome this limitation by using PTRMS to track toluene and other VOC degradation kinetics in the chamber. The results have provided baseline VOC efficacy data for the GPCO that can be applied toward device optimization for specific VOCs, different sized indoor spaces, and various applications. From a product standpoint and beyond its VOC removal capabilities, the GPCO is attractive for the following reasons: (1) it does not emit ozone, (2) it operates at variable air flows and works better at higher air flows, (3) the device can be sized to fit applications where space is a premium, (4) it has a very low pressure drop, and (5) the use of UV-A LEDs avoids harmful deeper UV rays and allows for safer integration into applications that are proximate to occupants of indoor spaces.

A key conclusion of the study is that it is possible to collect useful information about devices like the GPCO in relatively straight-forward chamber tests that utilize a bypass duct. The methodology presented here provides a foundation that can be built upon to more fully understand and benchmark the performance, safety (i.e., the generation of by-products), and applicability of various air cleaning technologies. We believe this methodology can be leveraged in the development of improved standards for testing of air cleaners such as PCOs and assist with improving their acceptance in the market by customers and consumers.

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