

Analysis of Chemical and Physical Effects of Ultraviolet Bulbs on Cooking Emissions

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ABSTRACT

There is a growing recognition of the risks to health, fire hazard, and air quality from cooking emissions. Recent research has identified what is emitted when foods are cooked. Some of the emitted mass is captured in the exhaust system. The balance is expelled into the atmosphere. The outlet of the exhaust system is a demarcation point—upstream the captured mass is the operator or building owner's concern, whereas downstream into the atmosphere, it affects air quality. Building codes have long required operators to deal with the upstream section. More recently, regulations are being placed on what kitchens can emit to the atmosphere. The industry is responding to this challenge with product innovations. Recently gained understanding of cooking emissions supports much of the innovation—but not all. This paper evaluates the purported benefit of adding better filtration and ultraviolet C (UVC) bulbs in kitchen hoods. A "UV hood" claims a two-step process to reduce emissions: better filters capture more emitted mass, and UVC photons and ozone drive photo-decomposition and oxidation reactions of some of the remaining greasy constituents. Adding UV to a hood at least doubles the cost compared to an equivalent non-UV hood. There is evidence that UV hoods do reduce some emissions. The essential question is whether improved

performance is due to UV or relatively inexpensive, improved filters. Experimentation exposed an oleic acid aerosol, representative of cooking emissions, to UVC energy and ozone at higher concentrations and for longer exposure times than can occur in a UV hood. Particle-size and chemical changes were measured on samples collected with UV bulbs off and on. Results strongly indicate little change is happening and most emission reductions are caused by better filtration and not UV. The conclusion is that UV hoods fall short of claimed performance, and unreacted ozone may increase air pollution.

INTRODUCTION

Cooking emissions have been with us since our ancestors began using fire. Increasingly, there are situations in which cooking emissions must be controlled. Control methods have evolved for millennia, but the most significant advances have occurred only in the last few decades. The main drivers of innovation in commercial kitchen ventilation (CKV) have been fire safety, sanitation, and worker safety. Specifically, the CKV industry has introduced active fire-suppression systems, energy-saving designs and controls, automated hood cleaning, and improved worker comfort. But it is clear that further development should focus on how to deal with the problems and costs caused by greasy emissions.

Recent studies have measured what is emitted when various foods are cooked on a variety of appliances.^{1–4} Most attention has been focused on meat and fish because the cooking of these high-fat-content foods creates substantial quantities of grease in the forms of aerosols and vapors that can create fire, sanitary, and public health hazards. Some of the emitted solid and liquid aerosols are captured within the exhaust system whereas the balance of aerosols and noncondensing vapor are expelled into the atmosphere.⁵

In most cases, concerns about cooking emissions are shared among the party doing the cooking (operator), the building owner, and the public. The outlet of the CKV system, typically the exhaust fan, is an important demarcation point. Upstream (toward the cooking) the emissions and their associated risks and costs are the concern of the operator and building owner. Public concern begins once

IMPLICATIONS

Commercial cooking emissions present problems in certain locations because of odors, fine particles, and volatile organic compounds (VOCs). Air quality regulations are increasingly requiring emission reductions. One attempted innovation is to place improved filters and ultraviolet bulbs in kitchen hoods. UV and the accompanying ozone are claimed to photo-decompose and oxidize much of the emitted organic constituents to smaller components. Testing with a representative emission constituent demonstrates that UV has little effect in reducing the mass or composition of the emissions, and that relatively inexpensive, better filters are responsible for most reduction. Additionally, air pollution, due to created ozone, may be increased.

the emissions enter the atmosphere. Regulations^{6,7} have been developed and imposed in jurisdictions where the smoke, grease, and odor in cooking exhausts are considered a problem. This paper will deal mainly with the CKV system up to the demarcation point; however, we will also make a link to the public interest because of the nature of the emissions that pass this point.

CKV Emission Control Approaches

Physical Approaches. Filtration is the oldest and most common control method used in commercial exhaust hoods. Four mechanisms act on liquid and solid particles, including those in kitchen emissions⁸: (1) gravitational settling, (2) impaction, (3) interception, and (4) diffusion. Gravitational settling causes much of cooking's emitted mass to fall out of the thermal plume before it reaches the filters. The latter three mechanisms act on liquid and solid particles in the filters and through the balance of the exhaust system, including hood plenums, ducts, and exhaust fans. There is also heterogeneous condensation of some vapor on particles and on exhaust system components.

Common building codes and standards such as the International Mechanical Code (IMC) and National Fire Protection Association (NFPA) Standard 96 require that Type I hoods (for grease and smoke) include some form of filtration. Most in-hood filters are typically single-stage, baffle-type devices designed to meet Underwriters Laboratories Inc. (UL) fire-safety standards.^{9,10}

Throughout the last century, little was known, quantitatively, about how effectively any filter captured cooking emissions, but it was clear that filters captured only a fraction of emissions. The American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) and the CKV industry addressed this lack of a filter-performance test by funding the development of an American Society for Testing and Materials (ASTM) standard to test capture efficiency.¹¹ The standard was published in 2005.¹² Recognizing the need for and establishing this standard has accelerated filter innovation, with recent introductions of improved single- and multistage filters.^{13,14}

Chemical Approach. In the past decade, so-called ultraviolet (UV) hoods have been commercialized. These hoods have an array of UVC bulbs on the downstream side of the filters. The bulbs emit in the C wavelength range (100–280 nm) and produce ozone. This is an interesting attempt to use chemistry to reduce the risks and costs caused by greasy emissions. The claim made for UV hoods is that UVC photons, and ozone, react with the greasy emissions that pass through the filters into the UV zone. Brief exposure to UV and somewhat longer contact with ozone is said to either break up some of the large molecular constituents in the emission flow or completely oxidize some of the smaller species. This implies that by adding UV, a hood is transformed from an air-handling device into a chemical reactor. This reactor is said to drive the degradation of a significant fraction of relatively large organic constituents, in a fast-flowing exhaust, at relatively low temperatures (<200 °F). Of course, fire does this but at much higher temperatures. This performance is claimed¹⁵ and refuted¹⁶ in the trade literature but there has been a poverty of experimental data to support the claims.

UV's Progression from Demonstrated Effectiveness to CKV Use. UV light has gained a significant place in heating, ventilating, and air conditioning (HVAC) applications. It is widely used in health care, food processing, and other biosensitive applications to kill or substantially reduce the counts of pathogens in whole buildings, rooms, or workspaces. Its effectiveness in this germicidal role has been extensively tested and verified.¹⁷ UV works in this application because it simply disrupts the genetic code of the targeted pathogens, thereby preventing reproduction. The energy and residence time required to drive these biochemical reactions is sufficient, and the presence of more complex chemical reactions is not required.

UV Effectiveness Uncertainty. UV hoods that are listed to UL Standard 710 must include some form of flame-stopping filter that is classified by UL Standard 1046. Available UV hoods include a primary filter stage and usually include a secondary filter stage to capture some of the grease not stopped by the primary filter. Such a secondary filter, of proper design, can significantly reduce the mass of grease flowing into the hood plenum. A reduced quantity of grease in smaller particles alone will reduce the build-up of greasy residue in the hood and ducting regardless of whether UV is present.

This last point leads to the central question about UV hoods, namely, what portion of any grease reduction is the effect of the UV bulbs, and what reduction can be attributed to better filtration? This is an important economic and public policy question because adding UV to a hood at least doubles its initial cost and significantly increases its maintenance cost, yet only a small fraction of the cost premium comes from adding the improved filters. Is the low-cost, added filtration providing the majority of the benefit? If so, there is unnecessary investment in the high-cost UV components and their related maintenance requirements. Until the research described in this paper, there has been no peer-reviewed experimental assessment of these claims.

Public policy decisions are being affected by the "UV effectiveness question". Some regulating and specifying bodies are considering requiring, or have already required, UV hoods in some new installations. If the claimed chemistry does not happen to any practical extent, then capital is wasted, and expensive mandates are being created based on bad assumptions and the intended emissions reductions, if any, will be due to better filters.

An earlier report by one of the authors (Farrell), based on the peer-reviewed literature, has described where the claims about UV's benefits run onto the scientific shoals.¹⁸ That report acknowledges that UV and ozone will cause reactions to occur and create new molecular species. However, the reaction conditions in UV hoods, in particular, available energy and residence time, are substantially insufficient to drive organic reactions to the claimed end. This paper represents an experimental continuation of that study.

UV HOOD TESTING

The objective of the experimental program was to determine what chemistry happens, how much grease reduction happens, and what causes the reduction when a UV hood is used. The U.S. Environmental Protection Agency, ASHRAE, California Air Resources Board, National Science Foundation, and Chinese governmental bodies have all

funded cooking-emissions-characterization and source-apportionment studies.^{19,20} The experimental program described below is informed by close study of these works and in many cases follow-up discussions with the researchers and authors.

Reactions require an input of reactants and energy to produce various end products. Both reactants and energy are present in actual cooking and in these experiments. Cooking produces literally thousands of potential reactants.^{21,22} Ozone created by the UV bulbs is another reactant. Ambient and appliance heat together with UV photons are the energy sources. The type and extent of reactions that happen are determined by concentration, chemical potential, available energy, and residence time. A reaction reaches completion (its end point) when the reactants have gone to their lowest free energy under the conditions present. The end point for complete oxidation (i.e., burning) of a hydrocarbon occurs when the starting material has been converted to carbon dioxide and water. More energy, a higher concentration of reactive materials, and a longer time all favor reactions proceeding to completion.

Experimental Program: Aerosol

The program used chemical and physical tests to evaluate the effectiveness of UVC bulbs in a hood. The testing was conducted in a purpose-built duct illustrated in Figure 1. Two UV light baffles (standard commercial kitchen grease baffles painted black) were used in the first and fourth filter slots to define the UV reaction zone. The UVC source was located in the center of that zone between the second and third filter slots. The duct design also allowed the testing of capture efficiency of commercial kitchen filters.

Experiments were run in a purpose-built test duct rather than in a hood and with a single surrogate material, namely oleic acid, rather than actual cooking emissions to better control experimental conditions and to provide consistency. Although this controlled environment does not include the combustion products present in gas-fired cooking, it is sufficiently representative of electric cooking to allow the intended evaluation of UV and ozone's effects. Moreover, as demonstrated in Gerstler et al.,¹ gas-fired cooking emits significantly more mass as aerosols and vapor than electric cooking, so any contribution to grease oxidation by combustion products seems negligible.

Aerosol Experiments. The aerosol particle size distribution in these experiments was very similar to actual cooking.^{23–25} Unless otherwise noted, testing was done at a flow rate of

200 cubic feet per minute (CFM) through the system. This is purposely at the low end of flows typical in working hoods. The flow was measured with a hot-wire anemometer using a 24-point traverse and controlled with the variable speed fan. Ambient laboratory air was heated to 100–110 °F with four 1500-W electric heaters. This temperature range maximizes ozone output of the UV according to the bulb manufacturer's specification.

A modified TSI Model 3450 (TSI, Shoreview, MN) vibrating orifice aerosol generator (VOAG) was used to produce an oleic acid aerosol, passing it through the reaction zone with no UV or ozone present, then capturing samples of the flowing material as liquid droplets and vapor, and finally, chemically analyzing the samples. These tests were repeated with UV and ozone present. The test duct was designed purposely to favor reaction of the flowing organic aerosol. Test conditions subjected the flowing aerosol to longer exposure by UV radiation and higher concentrations of ozone than is found in UV hoods, including hoods operating at low exhaust flow rates. Table 1 compares the UV energy, ozone concentration, and exposure time that an aerosol experiences as it flows through an actual UV-equipped system versus what is experienced in the test duct.

Oleic acid was used as the challenge aerosol. It is an omega-9 fatty acid ($\text{CH}_3(\text{CH}_2)_7\text{CH}=\text{CH}(\text{CH}_2)_7\text{COOH}$) found in various animal and vegetable sources. It is classified as mono-unsaturated because it has only one double bond. As the cited references demonstrate, many long-chain fatty acid compounds are common in cooking exhausts. Some are saturated, containing no double bonds, whereas others are polyunsaturated with multiple double bonds. Double bonds are the most reactive sites in this class of compounds and, in general, unsaturated compounds will react under milder conditions than saturated ones. In one study of hamburger-cooking emissions,²³ oleic acid was present in the greatest quantity of any fatty acid. It was selected for the study because of its relative abundance in actual cooking emissions and its ease of reaction.

The challenge aerosol was passed through an isotopic neutralizing chamber with six Staticmaster 2U500 isotopic neutralizers (new at start of experimentation, polonium-210 has a half-life of 138 days), through Tygon tubing and a copper tube into the top of the test duct. The copper tube introduced the aerosol parallel to the airflow at the center of the test duct two inches downstream from the face of the high efficiency particulate arrestance (HEPA) filter.

The aerosol then passed through a UV-light baffle, mimicking the mixing experienced by cooking emissions

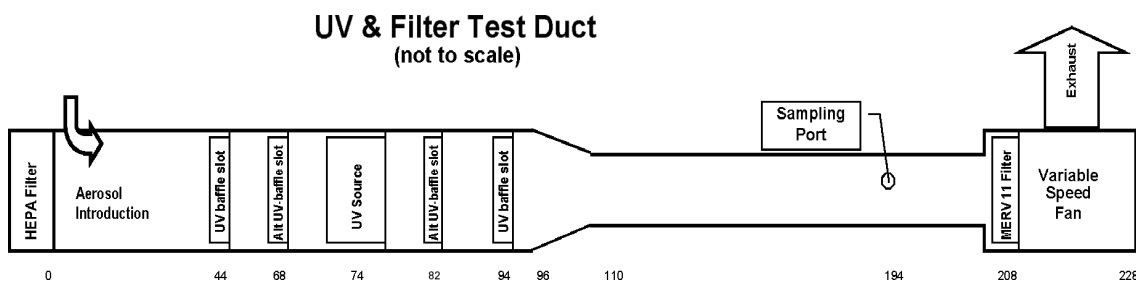


Figure 1. Test duct (not to scale). Duct lengths are in inches along bottom edge. Left section up to transition and fan section have a 24-inch interior square cross-sections. Connecting duct has a 11.75-inch inside diameter.

Table 1. UV and ozone exposure comparison in UV hood and test duct.

Typical 6' hood w/ (6) 64" UV bulbs					
Flow volume per front length, ft ³ /min/ft (m ³ /min/m)			250 (23.2)		
Front width, ft (m)			6 (1.83)		
Hood flow volume, ft ³ /min (m ³ /min)			1500 (42.5)		
UV energy, watt-hr* (Joules)			198 (7.13 × 10 ⁵)		
Ozone produced, gm/hr*			43.2		
Ozone exposure, mg/ft ³ (mg/m ³)			1500 (42.5)		
Test duct					
Flow volume, ft ³ /min/ft (m ³ /min/m) (per log-Tchebycheff Rule)			200 (5.7)		
UV zone length, ft (m)			4.0 (1.22)		
Ozone exposure length, ft (m)			9.8 (3.0)		
UV energy, watt-hr* (Joules)			34 (1.22 × 10 ⁵)		
Ozone produced, gm/hr*			9.2		
Ozone exposure, mg/ft ³ (mg/m ³)			0.77 (27.1)		
*per manufacturer's specification					
Exposure Condition			Time (sec)	UV energy (joules/m ³)	Ozone (mg-sec/m ³)
Hood					
Minimum contact interval	for UV irradiation		0.1	28	
	for Ozone in hood & ducting		0.4		7
Maximum contact interval	for UV irradiation		0.4	112	
	for Ozone in hood & ducting		2.5		42
Test Duct contact interval (200 CFM)	for UV irradiation		3.3	1320	
	for Ozone from bulbs to probe		4.6		125
Exposure ratio in test duct compared to hood					
Test duct compared to hood at maximum flow rate	for UV irradiation				47
	for Ozone in hood & ducting				18
Test duct compared to hood at minimum flow rate	for UV irradiation				12
	for Ozone in hood & ducting				3

as they flow into the UV zone of a hood plenum. In UV-on runs, ozone from the UV bulbs joined the flow, was mixed with the aerosol as it passed through a second UV-light baffle, and continued down the test duct to the sampling port. Samples of particulate matter were captured using HEPA grade, 47-mm, glass-fiber filters. A filter holder with a 0.56-inch nozzle on the front end was used to sample the flow stream isokinetically at 13.0 L/min. Samples were collected for 30 min for UV-on and UV-off experiments.

In separate experiments, samples of vapor and semivolatiles were captured using two different sorbent tubes. An XAD-2 sorbent (SKC, Inc., Eighty Four, PA) was used to study aldehydes whereas an Anasorb 727 sorbent (SKC, Inc., Eighty Four, PA) was used to capture VOCs. Ozone scrubbing sections filled with granular potassium iodide were used ahead of the analyte sections to prevent contamination and postcollection reactions from trapped ozone. Samples were taken in the center of the duct at the same point the particulate samples were taken (Figure 1). The flow through the sorbents was set at the supplier's recommended rate of 2.0 L/min and samples were collected for a total of 20 min.

Experimental Program: Other

Ozone Concentrations, Created by the UV Bulbs, with and without Aerosol Flowing. Ozone measurements were taken during the testing at various conditions and in various locations; however, the results reported below were all

taken with an ozone meter using a Teflon tube to sample at the center of the duct 4 ft downstream from the UV bulbs. Ozone concentration was measured with UV always energized. Readings were taken with no aerosol flowing then with aerosol flowing.

Particle Size Distribution Comparison of UV-Off versus UV-On Conditions. Particle size distributions of flowing aerosols were measured with two laser particle counters (LPCs) under two sets of test conditions. Both sets had data taken with UV-off and then UV-on. Samples were taken isokinetically at the center of the round duct at 7 ft (>7 duct diameters) from the end of the square to round transition. The first set was run using a Lasair Model 101 unit that measured in the 0.1–3.0 micron range at flow rates of 350, 590, and 878 CFM. Testing was done at room temperature because insufficient heating was available at these relatively high flow rates. The second set was run at a flow rate of 250 CFM at approximately 105° and measured with a HIAC/ROYCO 5230 LPC.

Filter Capture Efficiency. This test series measured the reduction in aerosol particle counts caused by UV and ozone acting alone compared to the capture efficiency of six commercially available kitchen filters in common use. Filters tested included four types used as primary filters in UV hoods, one type that is representative of the expanded-metal ("mesh") designs used as a secondary filter in UV

hoods, and one type that is a combined two-stage filter in a single unit. UV alone was also tested as a “filter” without any other filter(s) in place. These capture tests were conducted with procedures as similar as possible to ASTM F2519-05 *Standard Test Method for Grease Particle Capture Efficiency of Commercial Kitchen Filters and Extractors*, limited by the different geometry and source.

For filter testing, two mixing baffles were placed in the first and second slots of the test duct and the filter to be tested was placed in the fourth slot. The flow rate was 600 CFM with a filter face velocity of approximately 240 ft/min. The flow rate was measured with a hot wire anemometer using a 24-point traverse per U.S. Environmental Protection Agency (EPA) Standard 40 CFR 60. Pressure drop across the filters was measured using a digital manometer.

Energy Output Comparison of UV New and Dirty Bulbs. The UV energy output of clean and dirty bulbs (after exposure to greasy aerosol flows) was measured using a Hamamatsu UV power meter. The data were taken with separate sensors reading at 254 nm and 185 nm wavelengths. These were placed 0.5–0.75 inch from the bulb being analyzed. This testing required accessing the duct to place the sensors causing the air temperature to fluctuate. The UV energy output was recorded as the duct air temperature reached a point between 102 and 106 °F.

RESULTS AND DISCUSSION

Chemical Changes

Sample Collection. The stability of the aerosol generation and sample collection systems was evaluated by comparing the mass collected with the mass of oleic acid that passed through the aerosolizing system. In multiple experiments with the UV lamps off, the system collected an average of 0.027%, with a range of 0.020–0.037% ($n = 4$). With the UV lamps on, the system collected an average of 0.030%, with a range of 0.023–0.034% ($n = 3$). The two averages were not statistically different (t test for equal variances, $\alpha = 0.05$). One sample from each operating mode (UV-off and UV-on) was submitted for chemical testing. An analysis of blank filters (no oleic acid aerosolized) produced mass changes that were less than 0.001%. These gravimetric results alone strongly suggest that no significant decomposition to volatile products is occurring in the presence of UV light and ozone. Although the system did produce some chemical reactions (see below), these changes were consistent with the known reaction chemistry of oleic acid and other unsaturated compounds.

Analytical Methodology. Liquid- and vapor-phase samples were analyzed with gas chromatography–mass spectrometry (GC-MS) and Fourier transform infrared spectroscopy (FTIR). This chemical examination focused on identifying the presence of oleic acid and related degradation products. These analyses were performed by a laboratory that operates under International Organization for Standardization (ISO) 9001:2008 Certification.

Each filter sample was cut into two approximately equal portions. One portion was used for GC-MS analysis whereas the other portion was used for FTIR analysis. Each

Table 2. GC-MS sample weights.

	Filter Sample UV-Off Sample No. 1000851-01	Filter Sample UV-On Sample No. 1000851-02
FTIR sample	8.4 mg	9.5 mg
GC-MS sample	7.7 mg	7.6 mg

filter half was weighed to the nearest 0.1 mg (Table 2). The FTIR spectra were essentially identical, indicating no gross differences in chemical composition of the collected residues for the UV-on and UV-off experiments.

Each filter was then placed into a precleaned volatile organic analysis (VOA) vial. Chromatography grade methanol was added to each vial and allowed to extract at 37 °C for approximately 60 min. At the conclusion of the extraction, each filter was removed from the vial and dried overnight at 37 °C. The filters were dried to a constant weight and then weighed to the nearest 0.1 mg, with the filter weight loss recorded. The extract solutions for GC-MS analysis were then concentrated to 1 mL before analysis, whereas the extract solutions for FTIR analysis were concentrated to dryness.

Combining the split gravimetric data by filter from Table 2 indicates that the UV-off sample contained a total of 16.1 mg of collected material, whereas the UV-on sample contained 17.1 mg. These two mass values are considered approximately equal, considering the normal operating uncertainties in oleic acid feed rate and sampling procedures. As noted earlier, in multiple experiments the mass collected was not statistically different between the UV-off and UV-on experiments, and this sample was representative of those experiments.

This filtration-based sampling system is designed to physically capture liquid droplets and solid particles. Chemical components in the gas phase, including very volatile organics and gases such as carbon dioxide, will pass through the filter and will not contribute to the observed mass. These results alone strongly suggest that a significant number of volatile components are not being formed in the presence of UV light and ozone, and the total mass of nonvolatile components is unchanged when the UV lights are on.

Liquid Samples. The extract solutions were analyzed using GC-MS based on a modified EPA 8270 method. The semivolatile compounds were introduced into the GC-MS by injecting the sample into a 7890 Agilent gas chromatograph (GC) equipped with a 5975 mass selective (MS) detector with a scan range of 35–1000 amu. A DB-5ms narrow-bore capillary column was temperature programmed to separate the analytes within the GC, which were then detected with the MS detector as they eluted from the column.

A semiquantitative analysis was performed for all tentatively identified compounds. A computer-generated library search was performed by comparing the spectra of the unknown compounds with the spectra contained in the National Institute of Standards and Technology (NIST)

and Wiley reference libraries. A visual comparison was also made on each unknown compound and the best library match. Quantification was based on the response of the nearest internal standard. Where specific compounds could not be identified from the mass spectrum, the components were reported by the identified compound class (e.g., organic acid).

GC-MS is the "gold standard" for identification of volatile and semivolatile organic compounds. Its application in this setting provides an indication of the volatile and semivolatile chemical constituents that are present in the samples, and a tentative identification for many of them. Because reference standards were not analyzed, the concentrations of each constituent were estimated, and these estimates of quantities should be considered semiquantitative only. Thus, although mathematical interpretation of the absolute quantities is not appropriate, these estimates are valid for the present study, because the primary goal is to compare the two operating conditions. Differences caused by the UV light and ozone will be evident in the composition and overall mass distribution of the two extracts.

The UV-off sample as shown in Table 3 confirms the presence of oleic acid as the major constituent, but also indicates the presence of numerous other "unknown organic acids." These components are minor impurities (probably other fatty acids), and their presence is typical for compounds obtained from natural sources. The UV-on sample contains almost all of these compounds, as well as numerous other components, many of which have been tentatively identified. Many of these compounds are structurally related to oleic acid, and their formation is easy to rationalize based on simple chemical reactions. For

example, azelaic acid (nonanedioic acid), the next most abundant species in the UV-on sample, is industrially produced by ozonolysis of oleic acid. Similarly, nonanal and nonanoic acid are 9-carbon compounds, likely produced from cleavage of the reactive double bond in the middle of the 18-carbon oleic acid molecule. There is literature precedent^{26,27} for these reactions, and their presence in the UV-on sample is not a surprise.

The identities of these components confirmed that the UV and ozone of the test system were chemically reactive to oleic acid. A variety of reaction products were observed, indicating that numerous chemical reactions were occurring, including subsequent reactions of each reactant to form smaller compounds. In theory, this process could continue to occur for all reactants, eventually resulting in conversion of the organics to very small, volatile molecules. Although the formation of such volatiles cannot be discounted if exposure continued for a sufficient time (it was not determined in these samples), the fact that the majority of reaction products are larger molecules, and more similar to the parent oleic acid, suggests that significant conversion to volatiles is not a major degradation pathway for this system under these conditions.

Finally, the calculated mass results from the GC-MS experiment, and indeed the other gravimetric data, suggest that another reaction pathway may also be present in this system. A summation of all the mass values (i.e., total micrograms) for the UV-on sample in Table 3 is only about one-half of the corresponding total for the UV-off value. It is important to remember that the GC-MS experiment can only measure volatile and semivolatile components. Nonvolatile components, often represented by higher-molecular-weight compounds and other compound classes, will not be observed. Because the starting gravimetric values for the two samples were almost identical, these results suggest that a significant fraction of the UV-on sample consists of nonvolatile material.

Oligomerization and polymerization are examples of chemical reactions that produce nonvolatile products. A reactive monomer is needed, along with an appropriate catalyst. In this system, oleic acid has a reactive double bond that can be polymerized, in a manner similar to simple ethylene, which would form poly(ethylene). Ultraviolet light and ozone are both well-known catalysts for polymerization reactions. Thus, the creation of higher-molecular-weight species via a polymerization mechanism is a realistic possibility. Although all of the data suggest the presence of such polymeric species, determination of their actual presence would require additional experimentation. Again, previous studies^{26,27} under a variety of experimental conditions have confirmed the presence of the semivolatile species identified here, and suggested that the presence of larger, nonvolatile products is likely.

Vapor Samples. Vapor-phase samples were collected separately using sorbent tubes. Collection occurred with the UV bulbs off and for two different collection experiments with the UV bulbs on. Anasorb reagent was used to collect VOCs and the XAD-2 reagent collected aldehydes. Analysis of organic compounds in the vapor state collected with sorbent tubes was accomplished by GC-MS at the same laboratory. The front and back sorbent

Table 3. GC-MS results for liquid-phase samples UV-off and UV-on.

Tentatively Identified Compounds	Micrograms in Sample	
	UV-Off	UV-On
Hexanal	<1	2.6
Heptanal	<1	7.7
Hexanoic acid	<1	2.2
Heptane, 1-chloro	<1	1.1
1-Octanol	<1	1.1
Heptanoic Acid	<1	16
Nonanal	<1	57
Decanal	<1	1.1
Nonanoic acid	<1	3.5
2-Decenal	<1	2.7
Decanoic acid	<1	2.2
Dodecanoic acid	1.8	2.5
Azelaic acid	<1	360
Oleic acid	4700	1500
Sum of identified compounds	4714	1960
Unknown aldehydes	<4	240
Unknown organic acids	952	763
Unknown organic esters	4	9
Total of all species	5673	2972

Notes: Values listed as "<" were either not present or below the limit of detection for the system. The numerical value for the limit of detection was used in calculations to represent a worst-case scenario.

Table 4. GC-MS results for vapor samples.

Analyte	UV-Off, Anasorb (1001159-01) (µg/mL)	UV 25 Min Anasorb (1001159-05) (µg/mL)	UV-Off, XAD (1001159-02) (µg/mL)	UV 25 Min XAD (1001159-06) (µg/mL)	Anasorb 727 Method Blank (µg/mL)	XAD Method Blank (µg/mL)
Unknown	1.4	6.4	<1.0	<1.0	<1.0	<1.0
Nonanal	<1.0	8.6	<1.0	<1.0	<1.0	<1.0
Unknown aldehyde	<1.0	<1.0	<1.0	26	<1.0	<1.0

sections of each tube were removed and combined into one sample. Each sample was then extracted with a 50/50 mixture of methanol and dichloromethane. A blank tube for each sorbent was also extracted. Table 4 presents GC-MS results for vapor-phase samples. These readings indicate very little material in the vapor-phase with no UV light and only a slight increase in one experiment when exposed to UV. Overall, these results further confirm that large quantities of small, volatile organic compounds are not being produced in the presence of UV light.

Ozone-Consumption Testing. To measure the degree to which ozone produced by the UV bulbs reacted with the organic aerosol, its concentration was measured with particle-free air flowing, and then again with aerosol introduced. The small reduction in ozone concentration reported in Table 5 indicates that even in conditions where there is abundant greasy aerosol in fine particles to react with, only about 35% of the ozone is consumed. This is strong evidence that a large fraction of ozone does not perform the claimed grease reducing function, including on the smallest particles; rather, it is exhausted into the atmosphere where it is considered a pollutant.

Physical Changes

Particle-Size Changes. Actual cooking emissions and the test aerosol both contain a range of particle sizes. Changes in particle size distributions in the challenge aerosol with UV-off and UV-on offer a physical measurement of any effect that UV and ozone may have. Two tests were run to evaluate this. Figure 2a shows the aerosol at three flows for a particle size range of 0.3–3 microns, whereas Figure 2b shows the size range of 1–10 microns flowing at a single, slower rate.

These unchanging particle counts from UV-off to UV-on conditions shown in Figure 2a and b are further evidence that significant chemical decomposition is not

Table 5. Ozone concentration under several conditions.

	O ₃ (mg/m ³)	ppm O ₃
UV bulbs energized, temperature in duct 106 °F Airflow 200 CFM, Aerosol flow 4.1 g/min at generator		
Aerosol off	7.94	3.71
Aerosol on	5.15	2.41
Ozone consumption		35%

occurring. Any chemistry that happens to a particle will first change its surface chemistry and will often change its size. If UV were causing the claimed reaction, the effect would be seen most clearly on small particles because these have a large surface-to-volume ratio and would be the easiest to oxidize. If small particles were oxidized completely to carbon dioxide and water, they would be in the vapor state and not counted. It follows that if smaller particles are not being reacted to the vapor state, larger particles in the distribution are being affected even less. Note that when a particle's diameter doubles, its volume and mass increases by a factor of 8.

Capture Efficiency. Six commercial filters were successively challenged with the oleic acid aerosol. No UV was present. Particle counts were taken with the HIAC/ROYCO laser particle counter before, during, and after the period each filter was in place. Counts were also taken with only UV and ozone acting as a "filter". The data in Figure 3 show the particle count reduction provided by the several CKV filters in comparison to UV and ozone acting alone.

The two-stage filter demonstrated the greatest overall efficiency, the performance of several single-stage filters was impressive, but the UV and ozone removed essentially zero. This finding is consistent with the results shown in Figure 2a and b wherein UV and ozone did not change the particle size distribution.

Dirty UV Bulbs Reduce Available Energy. Another physical change measured was the energy output of the UV bulbs at 185 and 254 nm. Table 6 compares the output of new bulbs as well as the upstream- and downstream-facing sides of two bulbs used throughout the series of experiments. Energy output by UV bulbs is reduced upon exposure to aerosolized grease. The total amount of oleic acid used in the series of experiments was about 4 L. These data indicate that even a relatively small quantity of a cooking effluent reduces the energy available for photo-decomposition by coating the bulb. In an actual hood that experiences heavy loads of liquid and solid particles (e.g., grease and char), the energy output of the UV light will likely be reduced quickly.

Air Quality Hazard

One final point—it is important to consider the effect of UV hoods downstream of the demarcation point, the dividing line between the concerns of the operator and of the public. Indeed, the effect on air quality is likely to be adverse because a number of new compounds are

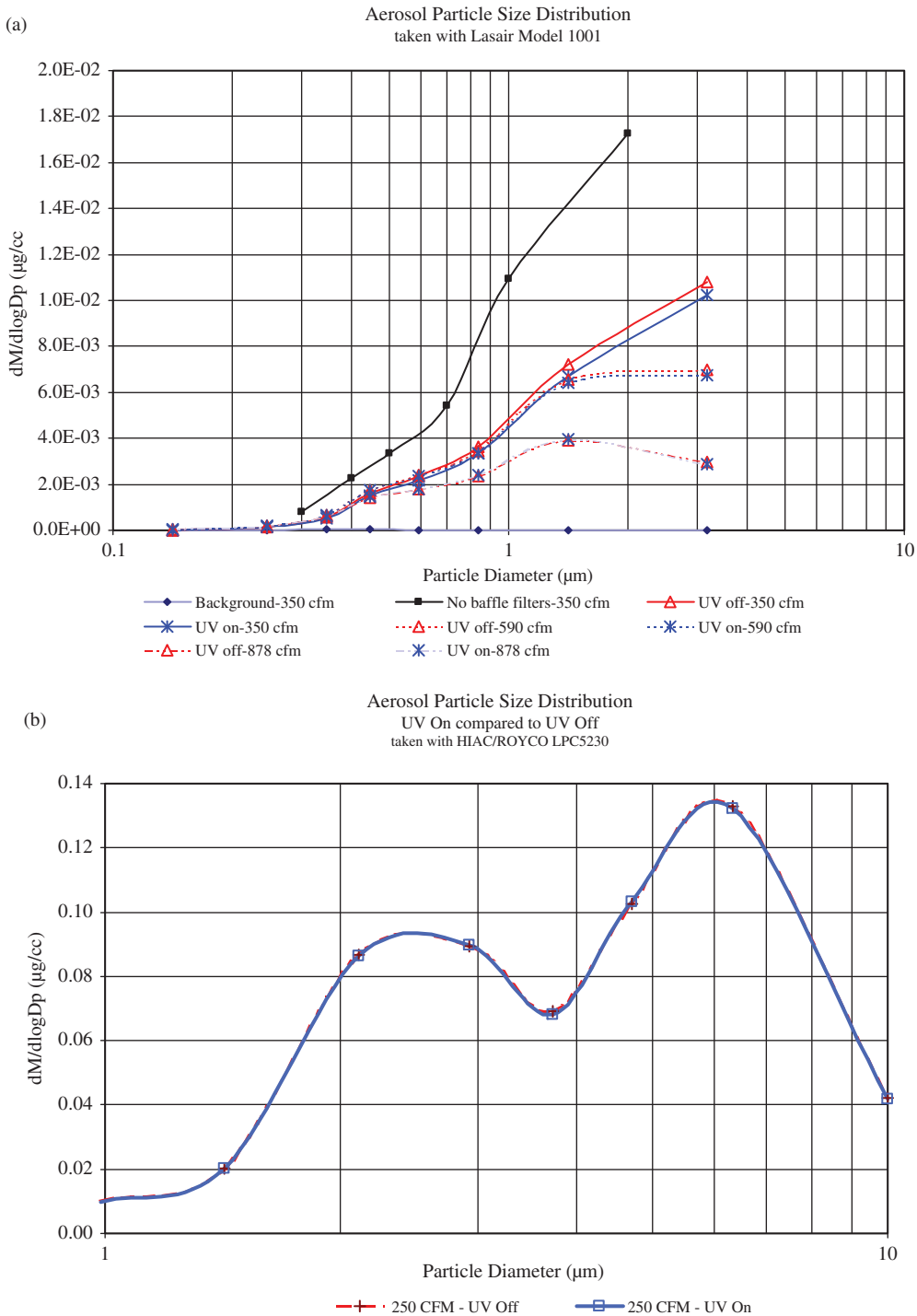


Figure 2. Comparison of aerosol particle size distribution, UV-off vs. UV-on. (a) Three flow rates of 350, 590, 878 CFM and background at 350 CFM for 0.1–3.0-micron particles, measured with Lasair Model 101. (b) Single flow rate of 250 CFM for 1–10-micron particles, measured with HIAC/ROYCO LPC5230.

formed, some of which are of lower molecular weight and more likely to be exhausted into the atmosphere, along with a significant fraction of the ozone produced by UV. Both the new compounds formed and the unreacted ozone have to be considered as contributors to air pollution. Further study of effluents under actual cooking conditions, with and without UV light, will be in the public's interest.

CONCLUSION

The analytical results exhibited in Tables 3 and 4 and the unreacted ozone reported in Table 5 all provide very strong chemical evidence that little reduction of the greasy mass is occurring in the presence of UV light and ozone. In the physical measurements, the virtually unchanged particle size distributions in Figure 2a and b and noncapture by UV in Figure 3 reinforce the chemical data. In all except

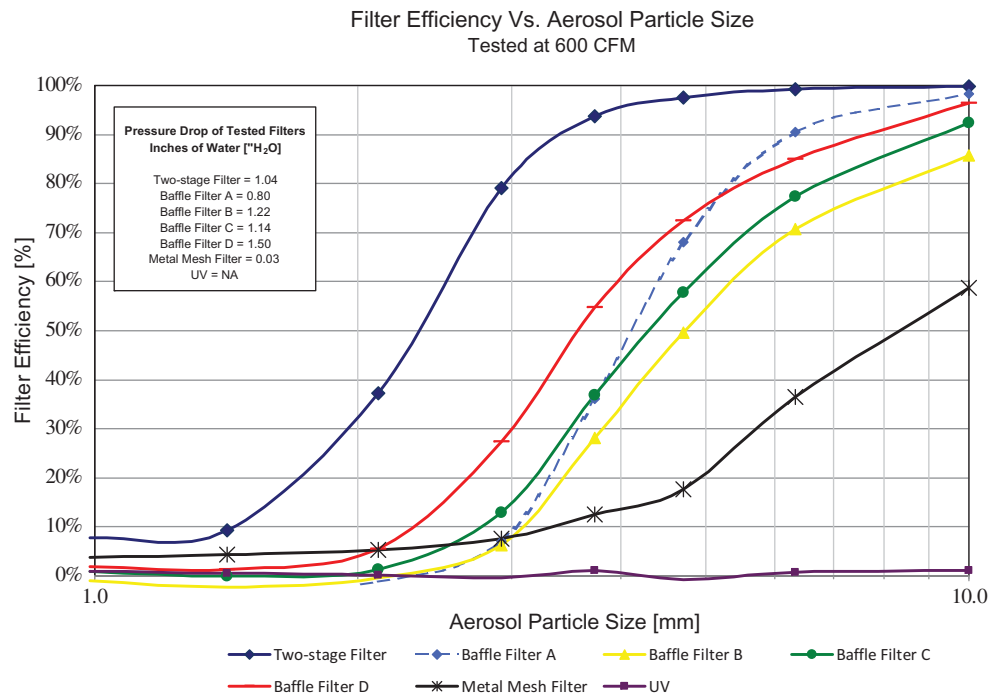


Figure 3. Particle capture efficiency comparison of six commercially available filters vs. UV and ozone.

Table 6. UV energy output of new bulbs, and clean and dirty sides of used bulbs.

Bulb (Wavelength, nm)	Upstream (Dirty) (mW)	Downstream (Clean) (mW)	Change (%)
1 (254)	10.58	12.00	-11.8%
3 (254)	12.52	13.63	-8.1%
3 (185)	2.07	2.37	-12.7%
New bulb (254)	n/a	13.45	n/a
New bulb (185)	n/a	2.54	n/a

the higher flow rates of Figure 2a, conditions are more favorable for reactions to occur than in an operating UV hood. As Table 1 shows, in these tests the challenge aerosol received exposure to UV energy between 47 and 12 times, and ozone exposures from 18 to 3 times, the conditions found in commercial UV hoods. If, in these conditions that strongly favor reactions, so little happens, it follows that the use of UV for real cooking offers no practical benefit. If UV hoods do, as claimed, remove grease from the effluent stream, it is clear from the testing summarized in Figure 3 that almost all grease removal is being performed by better filters before it is exposed to UV and ozone.

We conclude that the claims of significant UV-induced degradation of cooking effluents are not supported by the evidence gathered in this study. Although some chemical reactions are probably occurring, the majority of the effluent is unaffected by the presence of both UV light and ozone. Indeed, the data suggest that such reactions are

actually producing larger, less volatile products as well as smaller, semivolatile organics, rather than much if any carbon dioxide and water. Any real reduction in effluent mass through the system is likely the result of better physical filtration rather than chemical reaction. The use of UV light in CKV systems, then, represents an additional cost with no measurable benefit.

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