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Performance of ultraviolet photocatalytic oxidation for indoor air applications: Systematic experimental evaluation

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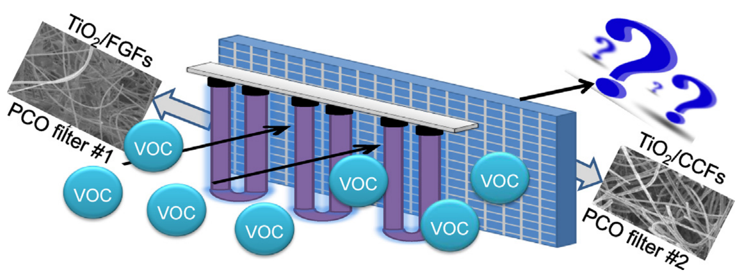
HIGHLIGHTS

- An innovative experimental set-up was designed and constructed for testing UV-PCO.
- Test methodologies were developed to examine UV-PCO air cleaners for VOCs removal.
- VOCs type, inlet concentration, flow rate, irradiance, and RH have influence on PCO.
- Gas-phase ozonation with a variety of compounds was examined in a duct system.
- Formation of by-products generated from incomplete conversion was investigated.

GRAPHICAL ABSTRACT



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ABSTRACT

Photocatalytic oxidation (PCO) is a promising technology that has potential to be applied in mechanically ventilated buildings to improve indoor air quality (IAQ). However, the major research studies were done in bench-top scale reactors under ideal reaction conditions. In addition, no study has been carried out on the investigation of the ozonation and photolysis effect using a pilot duct system. The objective of this study is the development of methodologies to evaluate the performance of PCO systems. A systematic parametric evaluation of the effects of various kinetic parameters, such as compound's type, inlet concentration, airflow rate, light intensity, and relative humidity, was conducted, and new interpretations were provided from a fundamental analysis. In addition, the photolysis effect under vacuum ultraviolet (VUV) irradiation for a variety of volatile organic compounds (VOCs) was examined for the first time in a pilot duct system. The performance comparison of ultraviolet C (UVC)-PCO and VUV-PCO was also discussed due to the presence of ozone. Moreover, the formation of by-products generated with or without ozone generation was fully compared to evaluate the PCO technology.

1. Introduction

Indoor air quality (IAQ) has received enormous attention for its impact on occupants' health, comfort, and work performance. Traditional dilution ventilation has limitation on protecting building occupants against chemical and/or biological agents and reducing energy consumption. The technology of adsorption filtration, such as granular activated carbons and zeolites, has been widely studied due to their promising removal performance. However, high pressure drop and adsorbent regeneration are the main obstacles in the applications of such adsorption air cleaners.

Heterogeneous photocatalytic oxidation (PCO), as a promising advanced oxidation technology, has been suggested as an

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alternative and energy efficient method to improve IAQ through the photocatalytic degradation of volatile organic compounds (VOCs) [1]. In literature, numerous researches have been carried out to examine the PCO of gaseous contaminants [2–7]. However, majority of available PCO data are based on laboratory bench-top equipped with a small PCO reactor where experiments were carried out under ideal reaction conditions, i.e. low volumetric airflow rates, tested with one or a few VOCs, etc. Therefore, the test results based on the ideal experimental conditions could be problematic and may not be scaled up to predict the performance in full-scale systems. Although a few researches have explored the feasibility of the PCO technology applied in HVAC systems [8–10], these applications are mainly aimed at designing a portable PCO air cleaner employed in a closed room or a chamber. Few studies [11,12] aimed to explore the PCO performance as a single-pass way employed in an HVAC system, and only several key parameters, such as residence time, irradiance type, and filter type, have been examined.

The application of ozone (O_3)-producing lamps in ultraviolet (UV)-PCO air cleaners inevitably introduces O_3 into a duct system. O_3 is a very powerful and strong oxidant. In the past half century, kinetics and mechanism of the gas-phase reactions of O_3 with VOCs under conditions relevant to the atmosphere were well examined in the atmospheric science field [13]. It is found that the action of O_3 is extremely selective, and O_3 usually plays a positive role to remove only alkenes and other VOCs containing unsaturated carbons. It is of interest to examine the ozonation effect in this project using a dynamic system with a relatively high O_3 concentration (ppm), rather than using a traditional static chamber system with a low O_3 concentration (ppb). Also, the photolysis impact on the removal of VOCs under VUV irradiation is an important photochemical phenomenon to be explored. Recently, a few studies investigated the removal performance of UV-PCO for toluene and benzene using a bench-top photocatalytic flow reactor with ozone-producing UV lamps [3,14,15]. To the best of our knowledge, no study has been carried out on the investigation of the ozonation and photolysis effect for a wide range of VOCs using a pilot duct system, which is one of the contributions of this study.

The principal objective of this research is to develop methodologies to evaluate the performance of UV-PCO systems for IAQ applications. Therefore, this paper demonstrates a systematic evaluation of in-duct UV-PCO air cleaners equitably and thoroughly under the conditions relevant to the actual applications for a wide range of VOCs. In addition, the ozonation effect on the performance of in-duct PCO air cleaners has been fully examined for the first time. Moreover, a parametric evaluation of the effects of various kinetic parameters, such as VOCs' type, inlet pollutant concentration, airflow rate, light intensity, and RH, on the PCO efficiency has been conducted for extending the existing knowledge on the PCO technology in indoor air applications. The formation of by-products generated from incomplete conversions has also been examined, which may have a profound impact on PCO technological developments.

2. Experimental

2.1. Materials

Two commercially available PCO air filters, titanium dioxide (TiO_2) coated on fiberglass fibers (TiO_2/FGFs) and TiO_2 coated on carbon cloth fibers (TiO_2/CCFs), were examined in this study. The physical properties of the two systems were characterized by scanning electron microscopy (SEM) for morphology and N_2 adsorption isotherm for BET surface area and pore structure, which are given in Table 1.

Table 1
Physical properties of TiO_2/FGFs and TiO_2/CCFs air filters.

Property	Units	TiO_2/CCFs	TiO_2/FGFs
Fiber diameter	μm	90	150
TiO_2 loading	wt%	14.32	4.63
BET surface area	m^2/g	887.7	105.7
Average pore diameter	nm	3.1	3.5
Total pore volume	cm^3/g	0.69	0.09

Low-pressure mercury lamps of each 18.4 W (Ster-L-Ray, Atlantic Ultraviolet Inc.) were employed: a G18T5L/U germicidal (UVC) lamp with a peak wavelength of 254 nm, and a G18T5VH/U ozone producing (VUV) lamp with a maximum emission at 254 nm and a minor emission at 185 nm. All lamps were powered by ballasts for ionization of the mercury vapor.

Eight reagent grade chemicals were selected as representative of indoor air contaminants [16], which included toluene (99.9%), p-xylene (99.9%), 1-butanol (99.9%), n-hexane (96%), octane (95%), MEK (99.9%), and acetone (99.5%) from Fisher Scientific Inc. (Canada), and ethanol (99%) from SAQ (Société des alcools du Québec – Québec Alcohol Board).

2.2. Experimental set-up

To develop a methodology for evaluating the performance of UV-PCO, an innovative UV-PCO system was built up, and the schematic diagram of the test apparatus is shown in Fig. 1. The test rig was made of four parallel aluminum ducts with 0.3 m × 0.3 m (1 foot × 1 foot) inner cross section area. The system was able to provide up to 255 m^3/h (150 cfm) airflow rates and was equipped with a radial fan with speed control mounted at the end of each duct. This was an open-loop mode system, and the laboratory air was introduced directly to the system after passing through a pleated fabric pre-filter. The air containing evaporated VOCs was introduced into the PCO system through a stainless steel tube and mixed with laboratory air at the gas mixer chamber. The conditions of inlet mixer gases were monitored for humidity and temperature by a sensor (HMT 100, Vaisala) mounted at the center of the mixer chamber. The well-mixed gases were evenly fed into four ducts.

The upstream of each of the ducts was fitted with a perforated stainless steel cross tube to collect air samples and an electronic low-flow probe at the center to monitor the airflow rate. The UV-PCO reactor was designed to be versatile, so that different in-duct UV-PCO filters with various geometries could be installed. In this study, three ducts were equipped with three PCO filters irradiated with four UV lamps arranged in two banks (Fig. 1). The vertical distance between the surfaces of the UV lamps and the PCO filters was approximate 5 cm, and the distance between two lamps was

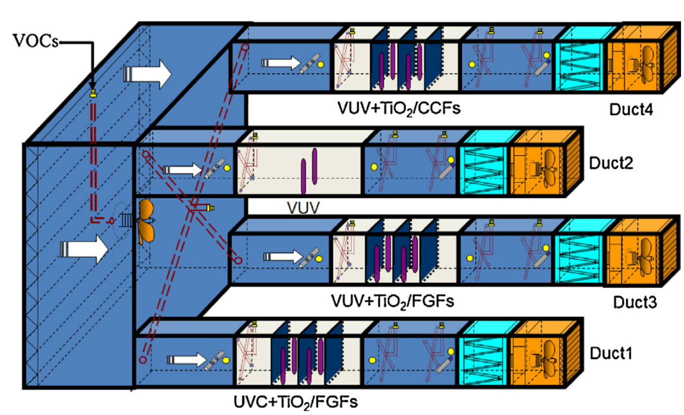

Fig. 1. Schematic diagram of the UV-PCO system.