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Assessing the Performance of Photocatalytic Oxidation of Volatile Organic Compounds in Three Different Scaled Set-ups

Zahra Shayegan¹, Chang-Seo Lee¹, Ali Bahloul², Melanie Huard², and Fariborz Haghighat^{1,*}

¹Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Quebec, Canada

²Institut de recherche Robert-Sauvé en santé et en sécurité du travail, Montreal, Quebec

*Corresponding email: Fariborz.Haghighat@Concordia.ca

ABSTRACT

Volatile organic compounds (VOCs) are considered a major group of indoor air contaminants with several proven adverse health effects. Ultraviolet photocatalytic oxidation process (UV-PCO) is a promising technology for the removal of VOC contaminants in indoor air environments. In addition, adequate efficiency of PCO has been proven in laboratory conditions. However, when PCO is scaled up and applied in real conditions, there are some limitations that need to be addressed. Several factors are involved in the efficiency of the PCO process such as humidity, flow rate (residence time), inlet of contaminant concentration, light source, etc. To the best of our knowledge, most of the research conducted in this area has been performed in a bench-scale reactor with long residence times of several minutes and at high VOCs concentrations (hundreds ppm level), which are far from being real indoor conditions. The main objective of this research is to study the scaling effect on isobutanol removal efficiency under the conditions relevant to real indoor applications. For this purpose, full-scale (0.6 m × 0.6 m), pilot-scale (four parallel ducts, 0.3 m × 0.3 m each) and bench-scale (9 cm × 7 cm) test set-ups were used to study the VOCs removal efficiencies via PCO in the gas phase. First, three experimental set-ups for testing TiO₂ photocatalyst are described. Then, the isobutanol removal efficiency is evaluated in the condition, which is close to the real application, considering the low-level contaminant concentration and high flow rate. The relative humidity in this study is kept in the comfort zone (RH ~ 50±5 %). The performance of UVC-PCO of the three scales is compared and discussed. For isobutanol with 0.003 mg/m³ inlet contaminant concentration, around 24%, 56%, and 68% removal efficiencies were achieved in the full, pilot, and bench-scale systems, respectively.

KEYWORDS

Photocatalytic oxidation (PCO), Volatile organic compound, Indoor air quality, Scale-up, Titanium dioxide (TiO₂)

INTRODUCTION

Volatile organic compounds (VOCs) are considered major contributors to air pollution and a cause of adverse health effects in humans. VOCs are found in the indoor air of residential and commercial buildings; they are released from building materials, consumer products, and occupant-related activity (Vildoza et al. 2011, Weon et al. 2017). Various techniques have been studied to remove VOCs, including adsorption, non-thermal plasma, catalytic oxidation, etc. (Huang et al. 2017a). However, these methods may have several drawbacks, such as generation of secondary pollutants, high energy consumption and high cost, which are obstacles when dealing with low VOCs concentration ranges (Ji et al. 2017).

Photocatalytic oxidation (PCO) is a promising technique, which can degrade various types of VOCs at low concentration levels (Huang et al. 2017b, Lyulyukin et al. 2018). Among different photocatalysts, TiO₂ is considered as one of the most efficient, because of its low cost, abundance, strong photo-oxidation power, and high chemical and photochemical stability (Ji et al. 2017, Weon et al. 2018). Our previous work summarized the PCO of several types of contaminants on TiO₂ photocatalyst surface (Shayegan et al. 2018). Accordingly, most of the published papers are based on bench-scale applications in laboratory conditions, whereas there is limited research on pilot or full-scale, which are applicable to real indoor application (Zhong et al. 2013). Small-scale investigations have often considered a high level of contaminant concentration and a low amount of flow rate with long residence time. Their results are not suitable for scaling up since they do not resemble real indoor air conditions (Shu et al. 2018).

This paper focuses on the effects of scaling up on the PCO process of a commercial filter. PCO of isobutanol at three different scales—including bench, pilot, and full-scale set-ups—are studied to determine the possible obstacles in scaling up the air purification process.

METHODS

Materials

In this study isobutanol (99.9%, ACS grade, Fisher Scientific, Canada) was used as the target contaminant. A commercial PCO filter was purchased from Saint Gobain Quartz Company. The 2,4-dinitro-phenylhydrazine (DNPH) cartridge and acetonitrile (HPLC grade) were purchased from Sigma Aldrich and Fisher Scientific, respectively for HPLC analysis.

Experimental set-ups

In this work, three experimental set-ups are used to investigate the effect of scaling up on the removal efficiency of the PCO process. Table 1 shows the operational parameters of these set-ups.

Bench-scale. The first experiment was carried out using a bench-scale duct. Fig. 1a shows the schematic diagram of the bench-scale set-up. The apparatus was made from an aluminum duct which had been anodized to have the highest reflectance to UV, with 7 cm × 9 cm cross-sectional area, 100 cm length, and 6.3×10⁻³ m³ volume. All the fitting and tubing used in the system were stainless steel or PTFE. For this set-up, two separate compressed air streams were used as the carrier gas and passed through the mass flow controller (MFC, OMEGA, FMA5442ST). The total flow rate of the duct was adjusted at 1.8 m³/h. Relative humidity of the system was controlled by passing one of the air streams through a vessel of distilled water. The second air stream was used to adjust the specific flow rate. The specified amount of isobutanol (see Table 1) was automatically injected by a syringe pump (KD Scientific, KDS-210, USA) into the duct. GC/MS (Agilent) and HPLC (Perkin Elmer) were used to analyze the contaminant concentration. Accordingly, GC and HPLC samples were collected to measure the isobutanol concentrations at the points upstream and downstream of the duct.

Pilot-scale. The second test apparatus used in this work is made of four parallel aluminum ducts, each with a 31 cm × 31 cm inner cross-sectional area. Fig. 1b depicts the schematic diagram of the test rig. As shown, the dimension of the closed part of the set-up is 3.6 m long and 1.2 m wide, with a total volume of 1.7 m³. The length of each duct is long enough to assume the air is following the ideal plug flow pattern. By using a radial fan, the system was able to control the speed of air and provide the flow rates up to 340 m³/h (200 cfm). Due to the size of the set-up, the laboratory air was used as the carrier air. The laboratory air, which

had passed through the filter, mixed with the air containing the evaporated isobutanol, was introduced into the system. The experimental set-up is an open duct system; therefore three humidifiers were used near the entrance of set-up to keep the relative humidity at a specified amount. The relative humidity and temperature at upstream and downstream of each duct were monitored by sensors (HMT 100, Vaisala) and recorded. The sensors were installed in two locations: at the center for upstream and past each duct's reactor sections for downstream. The cross-shaped sampling tubes were mounted at the beginning and at the end of the reactors to collect the upstream and downstream samples. GC and HPLC samples were collected to analyze the isobutanol concentrations at the upstream and downstream of each duct. Two pressure taps were installed, at the beginning and at the end of the PCO reactors for each duct. All of the probes and tubing used in the system were stainless steel or PTFE. The reactor was designed to be able to accommodate the various geometric shapes of the in-duct UV-PCO filters available on the market. Moreover, the design of these reactors allow for the changing of the number of lamps and catalysts. In this study, two layers of PCO filters and two UVC lamps were installed. The distance between the surfaces of catalyst and UV lamps was approximately 5 cm. In addition, the distance between each of the two lamps and the distance from each lamp to the reactor's wall were 13.3 cm and 8.6 cm, respectively. At the end of each duct, the clean-up section containing activated carbon, activated aluminum, and MnO₂ scrubbing filters was installed to capture the residual VOCs and any potentially generated by-products. The adequate numbers of MnO₂ layer post-filters were installed to control the exhaust ozone concentrations, less than 50 ppb.

Full-scale. The third set of experiments was carried out with a full-scale set-up, as presented in Fig. 1c. The duct was designed based on the ASHRAE standard 145.2 (ASHRAE 2016). The full-scale set-up has a 61 cm by 61 cm cross-sectional area, 11.5 m length, and 10 m³ volume. It is constructed of stainless steel with a smooth interior finish to minimize the absorption of contaminants on the internal surface of the duct. The design of the reactor offers the ability to test different types and sizes of air cleaning systems. As depicted in Fig. 1c, a radial fan with speed control (Rosenburg America, DKNB-355) is utilized which can provide an airflow rate up to 3400 m³/h (2000 cfm). A clean-up bed followed by a HEPA filter are installed, just past the fan, to filter out the possible particulate matter and aerosol from the carrier air. To reduce air leakage through the inlet or outlet dampers, ultra-low leakage positive pressure dampers (M&I Air Systems Engineering) were utilized in the system. The final clean-up bed was installed to adsorb possible by-products or unreacted contaminants before the exhaust is directly vented through the laboratory exhaust duct (Bastani et al. 2010).

Table 1: The operating parameters in the bench, pilot, and full-scale set-ups.

| Parameter | Value | | |
|---------------------|----------------------------------|----------------------------------|----------------------------------|
| | Bench-scale | Pilot-scale | Full-scale |
| Temperature | 23.5 ± 0.5 °C | 21 ± 0.5 °C | 23.5 ± 1 °C |
| Relative humidity | 50 ± 1 % | 47 ± 3 % | 48 ± 2 % |
| Air velocity | 0.5 and 1.25 m/s | 0.5 m/s | 1.25 m/s |
| Inlet concentration | 0.003 and 3.03 mg/m ³ | 0.003 and 3.03 mg/m ³ | 0.003 and 3.03 mg/m ³ |

RESULTS

The performance of commercial PCO filter for isobutanol degradation was evaluated under UV irradiation. The experimental data obtained from upstream and downstream of each set-up is employed to calculate the removal efficiency, η (%), as follow:

$$\eta(\%) = \frac{(C_{up} - C_{down})}{C_{up}} \times 100 \quad (1)$$

where $\eta(\%)$ is the single-pass removal efficiency and C_{up} and C_{down} (mg/m^3) are the contaminant concentrations at upstream and downstream of each set-up.

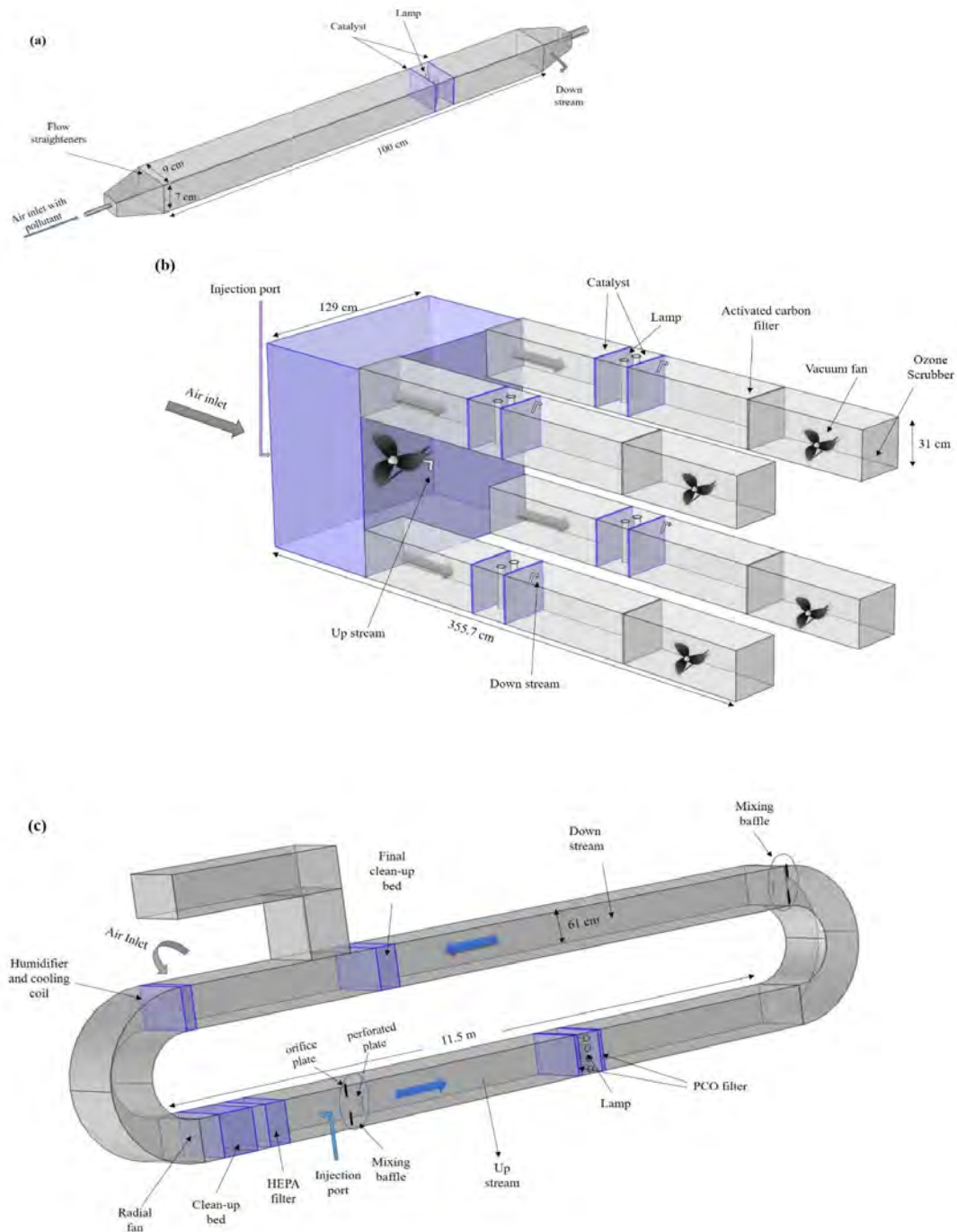


Figure 1. Schematic diagram of a) bench-scale, b) pilot-scale, c) full-scale set-ups.

Fig. 2a and b depict the removal efficiency of isobutanol at 0.003 mg/m^3 and 3.03 mg/m^3 , respectively, for bench, pilot, and full-scale set-ups. The velocity of air flow for pilot and full-scale was adjusted at 0.5 m/s and 1.25 m/s , respectively. In order to compare the results with bench-scale, two sets of experiments were conducted at 0.5 m/s and 1.25 m/s . As presented in Fig. 2a and b, the removal efficiency of isobutanol in low concentration is higher than in high concentration. Moreover, the removal efficiency of isobutanol decreased as the scale of set-up increased. The difference in results between setups of the same velocity may be a result of the effect of the light source. It is also observed that by increasing the air velocity, the removal efficiency was decreased, either in comparing two sets of bench-scale results or by comparing the pilot and full-scale ones. This is a result of the high air velocity, whereby the residence time is decreased and contaminant molecules have less chance to decompose in the shorter reaction time.

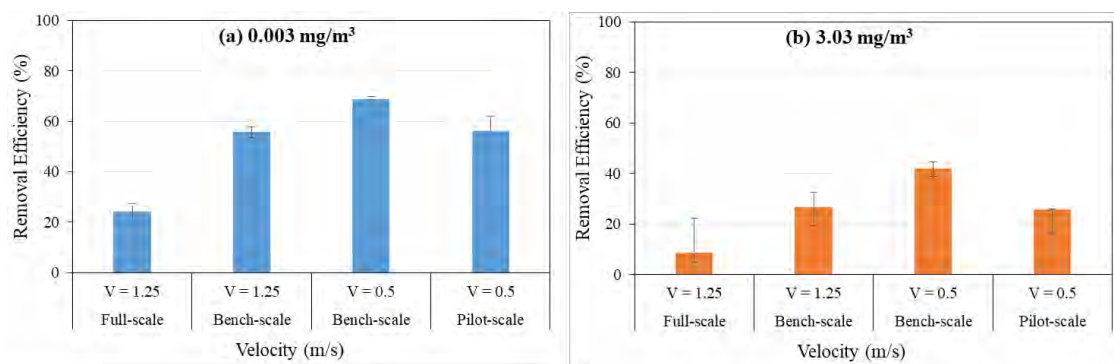


Figure 2. Removal efficiency of isobutanol a) 0.003 mg/m^3 , b) 3.03 mg/m^3 at three scale of set-ups.

DISCUSSIONS

The main problem in scaling up the photocatalytic reactor in large-scale applications is in having a uniform distribution of light irradiation for the entire photocatalyst's surface. The evaluation of light distribution inside the reactor is crucial for the extrapolation of laboratory scale results to pilot or full-scale operations. As mentioned in the results section, the lower inlet contaminant concentration showed higher removal efficiency. This occurs because the fixed active sites of the catalyst have limited adsorption capacity. Moreover, at high inlet concentration, the surface of the photocatalyst becomes saturated and quantum yield decreases due to the shielding effect of contaminants on the catalyst surface. In addition, increasing the airflow rate velocity causes a) the reduction in residence time of PCO process followed by decrease of removal efficiency, b) the increase of the mass transfer rate of contaminants to the surface of the catalysts, improving the PCO removal efficiency. It is obvious that laboratory-scale results are not sufficiently accurate and reliable for use in designing the UV-PCO system for indoor contaminants on a large-scale. Further studies need to be conducted to evaluate the effects of scaling up combined with indoor real conditions (e.g. multi-component mixtures) on by-product generation and catalyst deactivation.

CONCLUSIONS

Three scales of experimental set-ups were designed and constructed to study the UV-PCO performance of the commercial filter. In order to compare pilot and bench-scale set-ups, the experiments in bench-scale were conducted at 0.5 m/s velocity. The results showed that the removal efficiency in the bench-scale setup was higher than that of the pilot in both considered inlet concentrations. Additional experiments were performed at 1.25 m/s in bench-

scale in order to compare the results of the bench with full-scale. It is concluded that by increasing the air velocity and the size of the system, the removal efficiency of isobutanol was decreased.

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