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Deposition velocities and impact of physical properties on ozone removal for building materials

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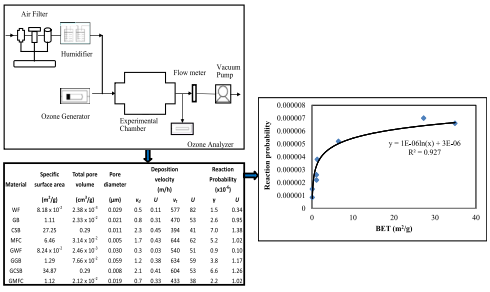
HIGHLIGHTS

- CSB showed the highest ozone deposition velocities among test materials.
- WF showed the lowest ozone deposition velocities among test materials.
- Green BMs are less reactive with ozone comparing with BMs except for GGB.
- Specific surface area of BM has a strong correlation with ozone removal.
- Ozone removal on building materials is internal diffusion-limited.

GRAPHICAL ABSTRACT



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ABSTRACT

This study aims to estimate the ozone deposition velocities of eight commonly used building materials (BMs) which include calcium silicate board (CSB), green calcium silicate board (GCSB), mineral fiber ceiling (MFC), green mineral fiber ceiling (GMFC), gypsum board (GB), green gypsum board (GGB), wooden flooring (WF) and green wooden flooring (GWF). In addition, the impact of physical properties (specific surface area and total pore volume of BM) on ozone removal ability was also explored and discussed. Studies were conducted in a small-scale environmental stainless steel chamber. CSB and GCSB showed the highest ozone deposition velocities, while WF and GWF showed the lowest ozone deposition velocities among test BMs materials. All reaction probabilities were estimated to fall within the order of magnitude of 10^{-6}. Green BMs showed lower reaction probabilities with ozone comparing with non-green BMs except for GGB. Consistent with the trends for deposition velocity, fleecy and porous materials exhibit higher reaction probabilities than smooth, non-porous surfaces. Specific surface area of BM is more closely related to ozone removal than total pore volume of BM with R^2 of 0.93 vs. R^2 of 0.84. Discussion of Thiele modulus for all test BMs indicates surface reactions are occurring quickly relative to internal diffusion and ozone removal is internal diffusion-limited.

1. Introduction

Ambient ozone exposure increases health risks such as cardiovascular effects, asthma symptoms and daily mortality (Romieu et al., 1997; Bell et al., 2004, 2006; Levy et al., 2005; USEPA, 2006; Jerrett et al., 2009; Peel et al., 2011; Devlin et al., 2012).

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Indoor concentrations of ozone are generally lower than outdoor due to reactions at building and occupant surfaces that consume ozone (Weschler et al., 1992). However, USEPA reported that the mean daily residential time spent indoors was 22.3 h in the USA, and the GerES II found that this duration was 20.9 h (USEPA, 1997; Song et al., 2008). Ozone is highly reactive, and heterogeneous indoor ozone chemistry can result in volatile carbonyls, particles and other reaction products which can be unhealthy and negatively affect perceived air quality (Klenø and Wolkoff, 2004; Morrison and Nazaroff, 2002; Reiss et al., 1995). Past researches about indoor ozone-material interactions have covered unused materials (Klenø et al., 2001; Grøntoft, 2002; Nicolas et al., 2007; Lamble et al., 2011; Gall et al., 2014), materials taken from field (Cros et al., 2012) and material experiments in the field (Wang and Morrison, 2006).

The ozone reactions with the materials are generally assumed to be first-order and can be characterized by the deposition velocity (v_d) that relates the bulk-air concentration to the flux of ozone to surfaces. The deposition velocity can be described by a transport limited deposition velocity (v_t) and a reaction limited deposition velocity (v_s) according to resistance uptake theory. However, Gall et al. (2014) pointed out two important limitations about this approach. First, deposition velocity calculations require a projected area that does not take into account the complexity of porous surfaces. Second, deposition velocity combines transport into and reactions within material substrates. For some materials and fluid mechanic conditions, these limitations may cause difficulty to recognize phenomena that affects estimates of ozone removal (Reiss et al., 1994; Klenø et al., 2001). Thus, Gall et al. (2014) took an experimental approach to investigate material characteristics and transport phenomena and their impact on values of Thiele modulus in terms of the challenges in estimating ozone removal on porous materials.

Direct comparisons of the effects of the physical properties are limited in the literature. In addition, green BMs have attracted significant interest in recent years. However, the reactivity of green BMs with ozone still requires further investigation (Hoang et al., 2009; Dafni et al., 2010). The aim of this study was to explore the ozone deposition velocities of eight commonly used building materials, including green building materials. Also, the physical characteristics and their impact on reactive uptake of ozone were discussed to further understand indoor ozone interactions with common building materials under typical indoor environment conditions. This is a first time to utilize new approach for describing and optimizing ozone reactions with real building materials.

2. Experimental methodology

2.1. Building materials

Eight kinds of building materials including calcium silicate board (CSB), green calcium silicate board (GCSB), mineral fiber ceiling (MFC), green mineral fiber ceiling (GMFC), gypsum board (GB), green gypsum board (GGB), wooden flooring (WF) and green wooden flooring (GWF) were selected for this study. “Green” specifically refers to low VOC emission building materials (i.e., after 48 h elapsed time, the formaldehyde emission rate is less than 80 μg m^{-2} $h^{-1}$and BTEX emission rate is less than 190 μg m^{-2} h^{-1}) which are rated by Taiwan Architecture and Building Center. All materials were unused and were shipped directly from three major manufacturers in Taiwan. Materials were wrapped in two layers of aluminum foil and one layer of plastic sheeting before experiments carried out.

All selected materials are commonly used for ceiling, cabinetry, and flooring. Each time only one kind of BM (30 cm × 30 cm) was placed in the environment chamber. The thickness is 0.9 cm, 0.6 cm, 0.9 cm, 0.9 cm, 0.7 cm, 1.1 cm, 1.2 cm and 1.2 cm for GCSB, CSB, MFC, GGB, GB, GMFC, WF, and GWF, respectively.

2.2. Experimental system

Laboratory experiments were conducted in a small stainless steel chamber. The electro-polished stainless steel chamber was designed under ASTM D5116-06 standard. A small fan was used to mix the air inside the chamber. Fig. 1 depicts the experimental system. The size of the chamber was 60 cm × 60 cm × 60 cm, and the experiment was set up at 25 °C, 50% relative humidity, and an air exchange rate of 0.5 h^{-1}. All air entering the chamber was pre-filtered through silica gel, activated carbon, and HEPA in order to get clean air (Lin et al., 2009). The air was pulled through a vacuum pump with a stable volumetric flow rate and was mixed with ozone generated by an ozone generator (2B Technologies, Model 306) with a precision of 1 ppb. The inlet ozone concentration was 75 ppb which is selected based on maximum 8 h daily average required by National Ambient Air Quality Standard (NAAQS). The mixed air was then conveyed through the chamber system. Inlet and outlet ozone concentrations were continuously monitored and recorded by UV ozone analyzers (2B Technologies, Model 202) with sampling time intervals of 10 s. Each experiment lasted for 8 h. The air flow rate of 1.8 L min^{-1} was confirmed after each experiment with a bubble flow meter (Sensidyne, Model Gilibrator 2) at the outlet of the chamber.

2.3. Determination of ozone removal efficiency

Each piece of BM was exposed to ozone at an initial concentration of 75 ppb for 8 h. Ozone concentrations inside the chamber was then continuously monitored and recorded by one UV ozone analyzer (2B Technologies, Model 202). Ozone removal efficiency (η) was determined by $1-C_{ozone,\ outlet}/C_{ozone,\ inlet}$, where, η: ozone removal efficiency; $C_{ozone,\ inlet}$: initial ozone concentration; $C_{ozone,\ outlet}$: final ozone concentration.

2.4. Determination of ozone deposition velocity

Based on the ozone mass balance of the chamber, ozone deposition velocity at steady state is calculated as Equation (1) shows. The ozone transport-limited deposition velocity can be found via Equation (2) assuming the amount of nitrate was completed converted from ozone reaction with coated nitrite which is highly ozone reactive so that ozone deposited at the transport-limited rate (Koutrakis et al., 1993). Associated experimental procedures to determine ozone transport-limited deposition velocity are referred to Morrison et al. (2003). Each piece of test BMs (30 cm × 30 cm) was coated with nitrite and exposed to ozone in the test chamber for 12 h. Uncertainty in ozone transport-limited deposition velocity based on replicate samples was around 10%. Equation (3) shows the calculation of ozone reaction probability given ozone deposition velocity and ozone transport-limited deposition velocity (Cano-Ruiz et al., 1993).

$$v_d = \frac{QC_{in} - QC_{ss}}{AC_{ss}} \tag{1}$$

$$v_t = \frac{M_{nitrate} MV_{ozone}}{CMW_{nitrate} A\Delta t} \tag{2}$$

$$\gamma = \frac{4v_d v_t}{(v_t - v_d)\langle v \rangle} \tag{3}$$