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Ozone removal on building material surface: A literature review

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ABSTRACT

Ozone is a reactive gas that can have negative health effects on human. Building materials can be significant sinks for indoor ozone, owing to the irreversible heterogeneous reactions between ozone and material surfaces. Therefore, the ozone removal on material surfaces is crucial for evaluating indoor ozone concentrations and human exposure. This paper presents a review of previous investigations on ozone removal on building materials. The reaction probabilities of common indoor building materials range from 10^{-8} to 10^{-4}, and depend on the material chemical compounds and surface characteristics. The surface-treated materials are probably more important than the underlying material substrate in determining ozone deposition velocities. Ozone removal on material surface is also associated with the fluid mechanics near the surface. Reactions between ozone and unsaturated organic compounds that constituting or adsorbed on material surfaces may result in oxidized by-products yields, while inorganic materials usually exhibit negligible by-products yields. Besides, the ozone surface removal on building materials under various conditions, i.e. ozone concentrations, air flow conditions, relative humidity and temperature, are discussed. Ozone removal on building materials after short-term and long-term exposure is presented.

1. Introduction

Ozone is a reactive gas that can have negative health effects on human, including increasing in respiratory-related morbidity, cardiovascular morbidity and premature mortality [1–17]. Weschler [18] presented that the indoor ozone concentration is dependent on the outdoor concentration, the air change rate, indoor ozone sources, and the removal by indoor surfaces and gaseous chemicals. In the absence of indoor ozone emission sources such as laser printers, photocopiers, and ionization/ozonolysis air cleaners [19–25], ambient outdoor ozone entering into buildings is the primary source of indoor ozone.

Buildings and aircrafts are usually the most typical indoor ozone exposure scenarios. Indoor ozone concentrations in buildings are generally below 50 ppb [26], while the concentrations in aircrafts can reach an elevated level of 300 ppb because of the high ambient ozone concentration in the air at typical cruise altitudes [27]. Usually, indoor ozone concentrations are lower than outdoor concentrations owing to the irreversible reactions at indoor materials and human surfaces that consume ozone [28]. The ratios of indoor to outdoor ozone concentrations are mainly in the range of 0.2–0.7 for most buildings according to numerous investigations [18]. However, albeit lower concentrations, indoor ozone exposures in buildings are around 43–76% of total daily ozone exposures [29], due to the fact that people spend average approximately 90% of their time indoors [30–33].

Building materials can be significant sinks for indoor ozone, owing to the irreversible heterogeneous reactions between ozone and material surfaces. The rate of ozone removal at the surfaces of building materials, which is typically quantified by deposition velocity, is governed by the transport of ozone to the material surface and the ozone uptake onto the surface [34,35]. Numerous researches have been conducted to study the ozone removal rate of some widely used building materials with the methods of laboratory experiments and field tests [35–40]. Available building materials studied in literature include glass, metals, ceramic materials, synthetic materials, finished floors, wallpapers, wooden boards, paints, ceiling tiles, concretes, cottons, wools, gypsum boards, carpets, activated carbon materials and bricks.

Reactions between ozone and material surfaces may also result in oxidized by-products yields, including C1-C13 carbonyls, dicarbonyls and hydroxycarbonyls [36–38,41–54], which can adversely affect occupants' health and perceived air quality [18,29,45,55–63]. These by-products are usually produced from reactions between ozone and the unsaturated organic compounds that constituting or adsorbed on material surfaces [29], while inorganic materials usually exhibit negligible by-products yields [37,38,45,64]. Some of these by-products with low vapor pressures can nucleate to new particles or condense on existing particles to form secondary organic aerosols (SOA) [65–68].

Recently, the investigations into ozone removal of passive removal materials (PRMs) have received increasing attention

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[35,37–39,44,45,64,69]. Compared to the conventional energy-consumed active filtration, passive removal materials such as activated carbon cloth, gypsum boards, carpet and clay based materials, can remove considerable indoor ozone through the chemical reactions between ozone and material surfaces without additional building energy consumption, and meanwhile form negligible by-products [35,37–39,44,45]. Therefore, PRMs have been considered to be an efficient and minimal energy-consumed passive control strategy for lowing indoor ozone concentrations and reducing human exposure.

There have been some detailed review articles focused on indoor ozone. Weschler [18,70–73], Salthammer and Bahadir [74], and Fadeyi [26] conducted reviews on previous researches about chemical reactions and products of indoor ozone. Weschler et al. [29,75] and Sundell et al. [76] highlighted the impact of indoor ozone on occupant health. Weschler [77] introduced the indoor ozone removal by human occupant. Darling et al. [64] presented a detailed review of the ozone surface removal on PRMs. However, these studies did not focus specifically on the ozone removal on common widely-used building materials. This paper attempts to provide the detailed reviews of the previous investigations on the surface removal of indoor ozone for a wide range of building materials. The ozone surface removal on building materials under various conditions are discussed.

The scientific literature reviewed in this paper was gathered by searching through ISI Web of Science (1900-present) and ScienceDirect (1823-present). In addition, Google Scholar was used as a supplementary search. As a source of search records, the following keywords were used: indoor ozone; surface removal; deposition velocity; reaction probability; building material; CFD simulation; mortality; morbidity; occupant health; ozone generation source; ozone surface chemistry; passive removal material; secondary emission.

Articles and publications were considered for inclusion based on the following criteria:

- Original research articles in English;
- Articles relevant to the key research questions identified;
- Publications up to December 2017;
- Articles without information on indoor air pollutants were excluded;
- Abstracts and purely descriptive articles without a detailed analytic component were excluded;
- Conference papers were excluded.

2. Mechanism and research methods

2.1. Mechanism

The level of indoor ozone concentration depends on the outdoor ozone concentration, air change rate, indoor emission rate, surface removal rate, and reaction between ozone and other chemicals in air [18]. Grøntoft [78,79] developed a group of multi-parameter models to describe the reaction of ozone on material surfaces, which consider the adsorption of ozone to materials, the desorption of ozone to air, and the diffusion of ozone into the materials. However, the majority of the published literature usually described the reaction of ozone to materials with a single-parameter mass balance model in an assumed well-mixed space, without considering the desorption of ozone to air and the diffusion of ozone into the materials. Based on the single-parameter model, the indoor ozone concentration can be defined by

$$\frac{dC_{in}}{dt} = P\lambda C_{out} + \frac{E}{V} - \lambda C_{in} - \sum k_{o3,j} C_j C_{in} - \sum \frac{v_{d,b} A_b C_{in}}{V} - \sum \frac{v_{d,h} A_h C_{in}}{V} \quad (1)$$

where C_{in} is the indoor ozone concentration (ppb), P is the ozone penetration factor (0–1), λ is the air change rate (h^{-1}), C_{out} is the outdoor ozone concentration (ppb), E is the emission rate of ozone into the space (ppb·m^3/h), V is the volume of the air indoors (m^3), $\Sigma k_{o3,j} C_j$ is the ozone removal rate by gaseous chemicals through chemical reactions (h^{-1}), $k_{o3,j}$ is the rate constant for the reactions between ozone and gaseous chemical j ($ppb^{-1}\cdot h^{-1}$), C_j is the indoor concentration of gaseous chemicals j (ppb), $\Sigma v_{d,b} A_b/V$ is the ozone removal rate by indoor building materials (h^{-1}), $v_{d,b}$ is the ozone deposition velocity of the building material (m/h), A_b is the surface area of the building material (m^2), $\Sigma v_{d,h} A_h/V$ is the rate at which ozone is removed by human surfaces (h^{-1}), $v_{d,h}$ is the ozone deposition velocity of the human surface (m/h), and A_h is the surface area of the human surface (m^2) (see Fig. 1). The surface removal of indoor ozone can be determined by the first-order irreversible surface heterogeneous reaction, which can be quantified by ozone deposition velocity (v_d). Ozone deposition velocity is a mass-transfer coefficient governed by the ozone transport to the surface and uptake by the surface, which is associated with fluid mechanics near the material surface and the chemical reactivity of the material with ozone [34]. The inverse of deposition velocity can be taken as an overall resistance to surface reactions (r_o), and is equal to the sum of transport resistance (r_t) and surface uptake resistance (r_s):

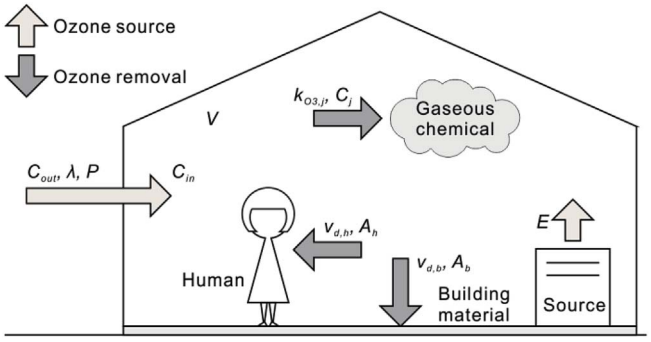

Fig. 1. Schematic illustration of indoor ozone source and sink.

$$\frac{1}{v_d} = r_o = r_t + r_s = \frac{1}{v_t} + \frac{1}{v_s} = \frac{1}{v_t} + \frac{4}{\gamma v} \quad (2)$$

where v_t is the transport-limited deposition velocity (m/h), v_s is the reaction-limited deposition velocity (m/h), γ is reaction probability (−), and $< v >$ is Boltzmann velocity for ozone ($< v > = 3.60 \times 10^4$ cm/s). The transport-limited deposition velocity depends on the boundary layer fluid mechanics near material surfaces. The reaction-limited deposition velocity can be quantified by reaction probability, which is the ratio of the removal rate to the collision rate of ozone on the surface. The magnitude of the ozone reaction probability is material specific and system-independent, which can be calculated by

$$\gamma = \left[\frac{v}{4}\left(\frac{1}{v_d} - \frac{1}{v_t}\right)\right]^{-1} \quad (3)$$

The values of γ range from as low as 10^{-8} for glass and metal to 10^{-4} for activated carbon and brick. Cano-Ruiz et al. [34] indicated that the surface removal of ozone is transport-limited when γ is larger than 3×10^{-4}, and reaction-limited when γ is smaller than 5×10^{-7} for typical indoor air flow conditions.

The by-products of reaction between ozone and material can be quantified by the molar yield (y_i), which is defined as the ratio of moles of the by-product i emitted from the material to moles of ozone removed by the material:

$$y_i = \frac{moles\ of\ i\ emitted}{moles\ of\ ozone\ removed} = \frac{\Delta C_{prod,i}}{C_{out} - C_{in}} \quad (4)$$

where C_{in} is the indoor ozone concentration (ppb), C_{out} is the outdoor ozone concentration entering into the building (ppb) and $\Delta C_{prod,i}$ is the increased concentration of the by-product i due to the reaction between ozone and material (ppb).