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Passive removal materials for indoor ozone control

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ABSTRACT

The indoor environment can contribute significantly to population exposure to ozone. This paper reviews the state of knowledge on building materials and coatings that are intended to passively remove ozone from indoor air. These passive removal materials, or PRMs, should have high ozone removal potential without significant and harmful reaction product formation. Ozone interactions with indoor environments, including surface and gas-phase reactions, known byproducts of these reactions, and health impacts of ozone and its byproducts are described. Research that has targeted PRMs for ozone removal is then summarized, and the materials in question are assessed in terms of their ability to reduce indoor ozone concentrations; ozone deposition velocities, reaction probabilities, as well as byproduct molar yields are presented and compared. This evaluation of the literature suggests that the most promising PRMs for ozone control are inorganic materials, including clay-based bricks and plasters, calcareous stone, and ceiling tile made of mineral fibers or volcanic perlite. Simple model equations are presented and used to highlight the potential for PRMs as a means for reducing indoor ozone concentrations. The removal effectiveness for ozone and reaction-derived formaldehyde is predicted for a commercially-available wall coating (clay paint) applied in a residential building. Removal effectiveness is also discussed in the context of required surface area and application costs for clay paint. A list of conclusions, limitations and research needs based on the existing knowledge base is also presented.

Contents

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1. Introduction

The indoor environment is a major determinant of human respiratory health, particularly given that Americans and those in many other developed countries spend on average almost 90% of their lives indoors [1–4]. Populations that are more vulnerable to respiratory health complications, e.g., infants, elderly, and the chronically ill, spend an even greater portion of their time indoors [5–7]. Poor indoor environmental quality has been linked to transmission of respiratory infections [e.g.,[8–10]], incidences of allergies and asthma [e.g., [11–13]], sick building syndrome (SBS) [14–18], and decreased productivity [19,20]. Fisk and Rosenfeld [19] estimated that the annual cost of respiratory infections, allergies and asthma, and SBS in the U.S. was roughly $103 billion, $22 billion, and $89 billion (all 2015 $), respectively.

Ozone can greatly affect the quality of the indoor environment. The primary source of indoor ozone is tropospheric ozone, which is a ubiquitous and reactive air pollutant that forms from reactions between oxides of nitrogen (NOx) and VOCs in the presence of sunlight. The health effects of ozone are well-known and significant. When ozone enters the lungs it reacts with epithelial cells and polyunsaturated fatty acids in fluids lining the lung, leading to the formation of by-products and subsequent inflammation and increased permeability of the epithelial lining fluid (ELF) [21–23]. Increases in ozone concentrations are associated with increases in respiratory-related morbidity and premature mortality [e.g., [24–29]]. Exposure to ozone has also been linked to increases in diagnoses of childhood asthma [30], school absences [31], and increases in hospital emergency room visits among children and the elderly [32].

Although outdoor ozone concentrations are typically greater than concentrations indoors, Weschler [33] estimated that 43–76% of human inhalation exposure to ozone of outdoor origin occurs indoors, and additionally that the average inhalation intake of ozone reaction products can be up to two times the indoor intake of inhaled ozone. Occupants of homes without centralized air conditioning systems may be at the greatest risk of exposure as the prevalence of these systems, and therefore lower air exchange rates and indoor ozone concentrations, have been shown to be inversely associated with ozone-related mortality [34]. Further, Chen et al. [35], in a modeling study encompassing 90 cities, predicted significant effects of indoor ozone on mortality. Logue et al. [36] estimated the burden of chronic exposure to average levels of indoor ozone (~9 ppb) to be equivalent to 6.7 (95% CI: 0.3, 160) disability-adjusted life-years (DALYs), or the years of life lost annually per 100,000 persons due to illness, disability, or early death. Aldred et al. [37] described the potentially high health benefit/cost ratios of ozone removal by activated carbon in HVAC systems.

Ozone is entrained into buildings via outdoor air intakes, cracks in the building envelope, or through open doors and windows. Some indoor environments may have devices that produce ozone, such as laser printers and photocopiers, ion generators and electrostatic precipitators used for air cleaning [38–40].

Indoor ozone concentrations, and therefore total inhalation exposure to ozone, can be reduced via active (i.e., energy-consuming) filtration methods such as treating building intake or indoor air using activated carbon filters [37,41–46]. Passive (i.e., no extra building energy consumption) removal methods can be employed by strategically placing ozone-scavenging materials or material coatings indoors.

Recent studies have focused on building materials or decorative material coatings (e.g., paint, plaster) for passive reduction of ozone [e.g., [47–50]]. These materials are referred to here as passive removal materials, or PRMs. The PRM concept is also being employed for other indoor pollutants, e.g., volatile organic compounds (VOCs) [51–59].

The concept of PRMs involves the application of select materials over large surface areas, generally walls and ceilings, onto or within which gaseous pollutants are effectively removed via adsorption (e.g., for VOCs) or irreversible chemical reaction (e.g., for ozone). In the case of VOCs, slow desorption generally occurs such that the PRM primarily affects the concentration-time profile. In addition to ozone, some other pollutants can be removed by reactions with material surfaces (e.g., chemisorption of formaldehyde to amino acids in wool [60,61]). The four main characteristics of PRMs are: (1) pollutant removal without consuming energy, other than the embodied energy in the production and manufacture of the material, (2) sustained pollutant removal over long time periods, (3) minimal reaction products released, and (4) practical use within buildings, meaning that the material can easily cover a large surface area while maintaining aesthetic appeal. To date, there are no published articles that summarize the state of knowledge related to passive removal materials. This paper serves as a review of the published literature that covers the concept of passive removal of indoor pollutant concentrations. We focus on building materials and coatings that may be used for removal of indoor ozone, assessing their ability to reduce indoor ozone concentrations without contributing significantly to total indoor emissions of volatile reaction products.

2. Background

2.1. Types and applications of PRMs

Yu et al. [62] were the first to express the utility of what were effectively PRMs for improving indoor air quality and conserving building energy. They focused on strategic placement of activated carbon sheets in buildings and modeled adsorption of select volatile organic compounds (VOCs) to those sheets in a hypothetical room. They emphasized the importance of placement of activated carbon sheets or other PRMs in locations where fluid mechanics are conducive to mass transfer. Sekine and Nishimura [63] studied multiple air-permeable glass fiber sheets pressed together and embedded with activated carbon and manganese oxide. Laboratory and field tests (six and seven months) in new apartments showed the potential for significant reductions in formaldehyde in apartment air using this PRM. Moriske et al. [64] also indicated that ozone removal was enhanced and the formation of formaldehyde reduced through the use of wallpaper coated on the back with activated carbon.

Ryhl-Svendsen [65] studied unfired clay bricks for reduction of pollutant concentrations in museum archives. The introduction of stacked clay bricks led to a 71% reduction in organic acid (formic + acetic) concentrations relative to room conditions prior to addition of the bricks. Total VOC and formaldehyde concentrations in the room were also reduced by 27% and 9.4%, respectively.

Degradation of VOCs by titanium dioxide (TiO_2), a non-structural photocatalytic material that can be used to coat or incorporate into building materials, such as mortars, mineral plasters, and wallpaper, has been investigated by several researchers [e.g., [51,66–70]]. Nomura and Jones [53–55] studied formaldehyde adsorption capacities of aminosilicas, and suggested that aminosilicas could be useful as indoor formaldehyde adsorbents, especially because no UV-light is needed. The National Research Council of Canada published a review of indoor air quality solutions and technologies, which highlighted a few options for passive control of indoor pollutants, including ozone, using large surface areas (i.e., walls) [71]. Included among these passive technologies were activated carbon media, anti-microbial wall coatings,